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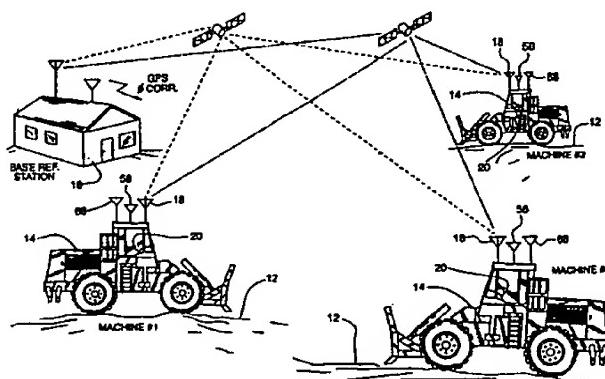
WORLD INTELLECTUAL PROPERTY ORGANIZATION  
International Bureau



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> : <b>E01C 19/00, E02F 3/84</b>		A1	(11) International Publication Number: <b>WO 95/28524</b>
			(43) International Publication Date: <b>26 October 1995 (26.10.95)</b>
(21) International Application Number: <b>PCT/US95/04432</b>		(81) Designated States: AU, CA, CN, JP, RU, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).	
(22) International Filing Date: <b>12 April 1995 (12.04.95)</b>		Published <i>With international search report.</i>	
(30) Priority Data: <b>08/228,837</b> <b>18 April 1994 (18.04.94)</b>		US	
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(54) Title: METHOD AND APPARATUS FOR MONITORING AND COORDINATION OF MULTIPLE GEOGRAPHY-ALTERING MACHINES ON A WORK SITE



(57) Abstract

An apparatus (40, 50, 60) and method (100, 101, 102, 104, 106, 108, 108a, 109, 110) for directing the operations of multiple geography-altering machines (14) on a common work site (12) relative to one another. Position information from several machines (14) is shared to generate a common, dynamically-updated site database (66) showing the machines' relative positions and site progress in real time. The common site database (66) is used to direct the operation of one machine (14) with respect to another machine or machines (14), for example by generating an operator display (22) of the site (12) showing relative machine position and total machine work on the site (12). The operator can accordingly adjust the machine's operation to avoid interference with other machines (14) or unnecessary overlap of work on the site (12). The information can also be used to coordinate the operations of several machines (14) in complementary fashion. Machine position information can be broadcast from the machines (14) to the site database (66) to create a common, dynamically-updated database (66) which is then shared with one or more of the machines (14). In a particular embodiment each machine (14) is provided with its own dynamically-updated database (66) and operator display (22), and machine position information is shared on a continuous, real-time basis between the machines (14) so that they effectively share a common site database (66).

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Description

METHOD AND APPARATUS FOR  
MONITORING AND COORDINATION OF MULTIPLE  
GEOGRAPHY-ALTERING MACHINES ON A WORK SITE

5      Technical Field

This invention relates to the operation of mobile geography-altering machinery on a work site and, more particularly, to the real time monitoring and coordination of two or more machines as they move over and work on the site through the creation of a common database of real time site update and machine position information.

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Background Art

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As used in this patent specification the phrase "geography altering machinery" and various approximations thereof refer to self-propelled mobile machines, for example compactors, track-type tractors, road graders, pavers and asphalt layers, which exhibit both (1) mobility over or through a work site, and (2) the capacity to alter the topography or geography of a work site with a tool or operative portion of the machine such as a compacting wheel, blade, shovel, bucket, ripper or the like.

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Caterpillar Inc., the assignee of this invention, has invented real time methods and systems for precisely determining the position of a mobile geography-altering machine as it traverses a work site and for creating a dynamically updated digital model of the site as it is altered by the machine. These systems improve the ability of an operator or site supervisor to monitor and control the operation of a single machine on the work site.

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The Caterpillar systems use a digital data storage, retrieval and process facility which may be

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carried on the machine for storing, creating and modifying a digital model of the site as it exists at any given time, as well as a digital model of the desired geography of the site. They further use a  
5 mechanism by which the exact position in three-dimensional space of the machine, or its operative portion, can be accurately determined in real time; i.e., as it traverses and alters the site thereby to update the site model, point by point and  
10 in real time. In a preferred implementation a phase differential GPS (global positioning system) receiver system is used which is capable of precisely locating  
~~a moving object in three-dimensional space to centimetre accuracy.~~ The digital process facility,  
15 e.g. a local computer, includes a dynamic site database and differencing algorithm which compares the desired site model to the continuously updated actual site model and generates signals representing the degree of alteration needed at each of a large number  
20 of coordinates over the site to bring the actual model into conformity with the desired model. The signals are used in one practical application to provide real time displays on the machinery to cue the operator as to the machine's actual position and progress in real  
25 time and within a frame of reference which conveys information as to at least a substantial portion of the overall site.

The site, or a practically displayable portion thereof, is subdivided into a continuous matrix of unit areas of such size that the machine may traverse these unit areas at a rate which is greater than the sampling rate of the GPS receiver and data processing facility. Algorithms are provided which take into account the physical parameters and  
35 dimensions of at least an operative portion of the

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machine and the relationship thereof to the machine in its path of travel. The unit areas of the display are filled in, coloured, revised or otherwise altered in accordance with progress information derived from the 5 GPS receiver and the digital processing facility. The real time path of the machine relative to the site between position readings is determined with a differencing algorithm which determines effective parameters of the operative portion of the machine 10 less than or equal to its actual parameters, and which updates each portion of the site model which the effective parameters traverse.

15 The present invention addresses the problem of coordinating multiple geography-altering machines as they operate on a common work site.

Disclosure of the Invention

According to the invention there is provided 20 apparatus for monitoring and coordinating the operations of multiple mobile geography-altering machines on a work site, the apparatus comprising:

site database means for storing data representing a site model of representing the geography of the site;

25 means for generating digital signals representing in real time the instantaneous three-dimensional site coordinate position of the geography-altering machines on a first machine and a second machine as they traverse and alter the site;

30 means for receiving said signals and for updating said site database means the site model in accordance with the said signals from the first and second machines to create a common site database; and

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means for providing control signals for transmission to said geography-altering machines in response to updating of said site database means.

5       The site database can be located remotely from the machines, or on one or both of the machines.

10      The mechanism for generating position signals asynchronously may broadcast the position signals from each machine to the mechanism for receiving the signals. The asynchronous broadcast means can further broadcast a machine-identification signal with the position signal.

15      The apparatus may include means for directing the operation of the machine which can comprise an operator display, for example a display of the site model and the position of the first and second machines on the site. The operator display can be located remotely from the machines, or on one or more of the machines.

20      The apparatus of the present invention can further include means for monitoring the operation of the first and second machines relative to one another to prevent interference between them. This can include means for defining a machine interference boundary around a machine to provide a warning signal 25 when the position or boundary of another machine is determined to be within that boundary.

25      Two mobile geography-altering machines can each be equipped with apparatus to generate signals representing in real time the three-dimensional position of the machine as it traverses and alters the site. Each machine may also provided with digital data storage and retrieval apparatus for storing a site model representing the geography of the site, and a dynamically updated site database for receiving 30 position signals and for updating the site model in

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accordance with the signals. Each machine can further be provided with apparatus for transmitting its position signals to the other machine, and for receiving position signals from the other machine.

5       The site database on each machine is then additionally updated with the position signals from the other machine to create a common site database. Apparatus may be provided for directing the operation of each machine relative to the other machine working on the 10 site in accordance with the common site database.

In a further aspect of the invention there is provided a method of monitoring and coordinating the operation of a mobile geography-altering machine on a work site relative to other such machines 15 operating on the site.

In a further embodiment of the inventive method, the position signals of each machine are asynchronously broadcast such that only one machine per unit time broadcasts its position signal to the 20 site database.

A machine-identifying signal can be broadcast with the position signal from each machine. The mixed position/ID signal from a particular machine can be matched with machine parameters to update the 25 site database in accordance with the specific characteristics of that machine.

Brief Description of the Drawings

Examples of apparatus and methods according 30 to the present invention will now be described with reference to the accompanying drawings, in which:

FIG. 1 is a schematic perspective view of a compacting work site with a base reference station and multiple compacting machines operating on the site;

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FIG. 2 is a schematic representation of a multiple machine coordination method according to the present invention;

5 FIG. 3 is a schematic representation of an apparatus which can be used in connection with the receipt and processing of GPS and machine position/ID signals to carry out the present invention;

10 FIGS. 4 and 4A are schematic representations of an embodiment of the apparatus of Figure 3 using GPS positioning and two-way radio communication between multiple machines;

FIG. 5 illustrates an asynchronous machine position broadcasting method;

15 FIG. 6 is a representative operator display generated by the system of the present invention for a landfill compacting operation;

FIGS. 6A and 6B are illustrative three-dimensional computer models of a site which can be used with the present invention;

20 FIGS. 7A-7K are flowchart representations of a dynamic site database with multiple machine coordination for a landfill compacting operation according to the present invention;

25 FIG. 8 is an alternate operator display which can be generated for an earth contouring application of the present invention; and

FIG. 9 is a schematic representation of an apparatus according to the present invention in a system with closed-loop automatic machine controls.

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Best Model for Carrying Out the Invention

Referring to Figure 1, a landfill compacting site 12 is schematically illustrated with a number of landfill compacting machines 14 of a known type operating over the site surface to compact it. In the

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illustrated embodiment each machine 14 is equipped with a three-dimensional positioning system and a dynamically updated site database for geography-altering operations. The site database includes a 5 digitized site model, for example a two- or three-dimensional topographical map of the site surface subdivided into a number of unit areas in known manner. As the machine positioning system determines and signals the position of machine 14, 10 traversing site 12 in real time, the site database is dynamically updated to reflect the machine position relative to the site and corresponding changes in the site topography, for example by noting elevation changes where the topography is raised or lowered by 15 the operation of the machine, or by incrementing a pass count comprising the number of passes by a machine over a unit area of the site. The dynamic database generates signals representing machine position and the updated site model, which signals can 20 be used to direct the operation of the machine, for example with a real time operator display and/or automatic machine controls.

In the illustrated embodiment the machines 14 are equipped with 3-D position information 25 apparatus 18 using kinematic GPS positioning. Primary position signals are received at 18 from the GPS satellite constellation orbiting the Earth and a differential/correction signal is received at 58 from base reference station 16. Information on kinematic 30 GPS positioning and a system suitable for use with the present invention can be found, for example, in U.S. Patent No. 4,812,991 issued 14 March 1989 and U.S. Patent No. 4,963,889 issued 16 October 1990, both to Hatch. Other 3-D positioning systems are known and 35 can be used, however, for example 3-D laser

positioning, GPS/laser combinations, or UHF/VHF radio.

Using kinematic GPS or other suitable three-dimensional position signals from an external reference, the location of receiver 18 and each machine 14 can be accurately determined on a point-by-point basis within a few centimetres as the machines traverse site 12. The sampling rate for coordinate points using the illustrative positioning system is approximately one point per second.

Accordingly, as each machine 14 traverses site 12 and performs its compacting operations, the operator of each machine is provided with accurate, real time machine position and site update information for that machine. Although the illustrated embodiment shows a landfill compacting operation, real time machine position and site update systems for geography-altering operations such as earth moving/contouring, grading, paving and the like are within the scope of the invention.

The present invention addresses the need for coordinating the movement and work of multiple machines 14 working on the same site 12. This is achieved by creating a common, dynamically-updated site database reflecting the real time position and site progress of multiple machines operating on the site, and using that common database to give a machine operator or supervisor accurate, coordinated, real time machine position and site update information for every machine operating on the site.

Real time machine position information is "shared" by each machine with the common database via suitable transceiver apparatus 68. The site database can then be used to direct the operations of as many machines as desired relative to one another. For example, as in the present example, each machine can

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be provided with its own individual site database in  
an on-board computer 20, that database being  
continuously updated with its own position information  
and with position information from every other  
5 machine, such that each database is essentially  
identical to that of every other machine at any point  
in time. Alternatively, a single database, located on  
one machine or adjacent the site at base 16, can  
receive position information from each machine, update  
10 the site database locally, and transmit signals to  
each machine to direct their operation, for example  
for generating an operator display of the dynamically  
updated site model on each machine.

Referring now to Figure 2, the method of the  
15 present invention is shown schematically with  
reference to a flowchart. Using a known three-  
dimensional positioning system as referred to above,  
machine position coordinates are determined in step  
100 as the machine moves over the site. These  
20 coordinates are instantaneously supplied as a series  
of discrete points to a differencing algorithm at 102.  
The differencing algorithm calculates the machine  
position and path in real time. Digitized models of  
the actual and desired site topography/geography are  
25 loaded or stored at step 104, in an accessible digital  
storage and retrieval facility, for example a local  
digital computer. The differencing algorithm 102  
retrieves, manipulates and updates the site models  
from 104 and generates at 106 a dynamic site database  
30 of the difference between the actual site and the  
desired site model, updating the actual site model in  
real-time as new position information is received from  
step 100. This dynamically updated site model is then  
made available to the operator in display step 108,  
35 providing real time machine position and site updates

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in human readable form. Using the information from the display the operator can efficiently monitor and direct the manual control of the compacting machine at 109.

5            Additionally, or alternately, the dynamic update information can be provided to an automatic machine control system at 110, for example an electrohydraulic control system of the type developed by Caterpillar Inc. and used to operate pumps, valves, 10 hydraulic cylinders, motor/ steering mechanisms and other controls used in geography-altering machinery. The electrohydraulic controls can provide an operator assist to minimize machine work and limit the manual controls if the operator's proposed action would, for 15 example, overload the machine. Alternately, the site update information from the dynamic database can be used to provide fully automatic control of one or more machine operating systems.

For the exemplary compaction embodiment 20 illustrated below, the desired site model is a predetermined desired degree of compaction of material on the site surface. The actual site model is the actual degree of compaction of the site material, ranging between an uncompacted state and the desired 25 degree of compaction. When the machine traverses the site in a compacting operation, the actual site model is monitored and updated in real time at 106 as the machine brings the actual site into conformity with the desired site model. For other site operations, 30 for example earth contouring using a blade-equipped tractor, the actual and desired site models may comprise the actual and desired surface contours of the site; the difference between them at any coordinate point is the difference in elevation at 35 that point. It will be understood that various site

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models for different site operations can be used with the present invention. Information on site modelling is commercially available.

Still referring to Figure 2, the method of the present invention may provide for the real time "sharing" of machine position information among multiple machines on the site, such that the machines effectively share a common site database of the position of each machine and the site alterations made by each machine. As a result, an unprecedented level of coordination and cooperation between multiple machines working on a single site can be achieved. For example, the operator(s) of the machines can monitor the relative proximity of machines to avoid unsafe conditions, and undesirable overlap of machine operations can be reduced or eliminated. Machine operations on the site can also be coordinated in a complementary manner, for example by directing several machines to perform successive operations on a portion of the site and updating the site database accordingly.

This is achieved in the method of Figure 2 at step 101 where machine position information, for example 3-D coordinate points in an (x, y, z) coordinate system, is received from a second machine by a suitable data transmission link. The multiple machine position information from blocks 100 and 101 is delivered to step 102, where the differencing algorithm calculates the position and path of both machines in real time and updates the site database at 106 accordingly. The resulting database displayed to the operator at 108 shows the positions of both machines on the site as well as the alterations to the site made by each machine.

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Additionally, the position information received for the first machine at step 100 can be retrieved from step 102 and transmitted at step 101 to an identical dynamic database being used to direct the 5 operations of the second machine. The dynamic database for the second machine is accordingly updated with position information from both the first and second machines as described above, and the resulting database displayed to the operator of the second 10 machine. In this manner the two machines effectively share a common, dynamically updated site database.

While the embodiment of Figure 2 illustrates a method where the first and second machines receive site update information from their own, separate, 15 commonly-updated site databases, it is possible to omit the transmission of machine position information at step 101 to another database. Instead, the dynamic site updates generated by the database at 106 can be shared directly with the second machine, for example 20 by transmitting signals to generate an operator display on the second machine as shown in phantom at 108a.

And, while the method of Figure 2 is illustrated for coordinating two machines, it will be 25 apparent that the number of machines which can be coordinated using this method is limited only by the rate at which the machine position information from each machine can be received and processed to update the dynamic database(s). For example, at step 101 30 machine position information could be received from and transmitted to a third machine, a fourth machine, a fifth machine, and so on.

In the illustrated method of Figure 2 the 35 position information for the second machine received at step 101 is input directly to the differencing

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algorithm at 102, and the position information for the first machine is retrieved from the differencing algorithm at 102. However, it is possible to input position information from the second machine directly 5 to a system position computer at 100 for subsequent delivery to the differencing algorithm at 102, and to receive position information for the first machine directly from step 100 for transmission to the second machine.

10 Referring now to Figure 3, an apparatus which can be used in connection with the receipt and processing of GPS signals to carry out the present invention is shown in block diagram form comprising a GPS receiver apparatus 120 with a local reference antenna and a satellite antenna for generating 15 position information for a first machine; a digital radio transmitter/receiver 122 for receiving position information from other machines; a digital processor 124 employing a differencing algorithm, and connected to receive position information from 120 and 122; a digital storage and retrieval facility 126 accessed and updated by processor 124, and an operator display and/or automatic machine controls at 128 receiving 20 signals from processor 124.

25 GPS receiver system 120 includes a satellite antenna receiving signals from global positioning satellites, and a local reference antenna. The GPS receiver system 120 uses position signals from the satellite antenna and phase differential correction 30 signals from the local reference antenna to generate position coordinate data in three-dimensions to centimetre accuracy for moving objects. Alternatively, raw data from the reference antenna can be transmitted to processor 124, where the 35 differential correction can be locally determined.

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This position information is supplied to digital processor 124 on a real-time basis as the coordinate sampling rate of the GPS receiver 120 permits. The digital storage facility 126 stores a 5 desired site model, for example a desired degree of compaction of the site according to a predetermined compaction standard, and a second site model, in an illustrative compacting operation the actual degree of 10 compaction of the site, for example uncompacted as initially surveyed. The actual site model can be accessed and updated in real time by digital processor 124 as it receives new position information from GPS 15 receiver 120.

Digital processor 124 further generates 15 signals representing the difference between the continuously-updated actual site model and the desired site model. These signals are provided to the operator display and/or automatic machine controls at 128 to direct the operation of the machine over the 20 site to bring the updated actual site model into conformity with the desired site model. The operator display at 128, for example, provides one or more 25 visual representations of the difference between the actual site model and the desired site model to guide the operator in running the machine for the necessary operations.

To generate a common site database useful 30 for coordinating multiple machines, the apparatus of Figure 3 is provided at 122 with a two-way digital radio capable of receiving position information from other GPS-equipped machines and providing it to the digital processor 124, and transmitting the position coordinates from the GPS receiver system 120 for the first machine. Digital processor 124 uses the 35 position information received by radio 122 in the same

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manner as the position information received from GPS system 120 to update the site database. Accordingly, the operator display at 128 will show the site position of each machine for which position  
5 information is available, as well as visual representations of the difference between the actual site model and the desired site model as determined or updated by each machine.

With multiple machines operating on a site,  
10 particularly where the machines are of a different type or size, it is desirable to encode a machine-unique ID signal with the position information from each machine. The ID signal is preferably stored in the database on each machine. The digital  
15 processor 124 can then identify each machine from which particular position information is being received. Where the machines differ in operating parameters or type, machine parameters corresponding to the machine-unique ID signal can be stored in  
20 digital storage and retrieval apparatus 126. The machine parameters are retrieved by the digital processor 124 and matched with an incoming position/ID signal to distinguish the machine on the operator display, to more accurately determine the path of a  
25 particular machine and the changes it may have made to the site, and its position.

Referring now to Figure 4, a more detailed schematic of a system like that of Figure 3 is shown using kinematic GPS for position reference signals. A  
30 base reference module 40 and a position module 50 together determine the three-dimensional coordinates of a compacting machine relative to the site, while an update/control module 60 converts this position information into real time representations of the site

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which can be used to accurately monitor and control the machine.

Base reference module 40 includes a stationary GPS receiver 16; a computer 42 receiving input from receiver 16; reference receiver GPS software 44, temporarily or permanently stored in the computer 42; a standard computer monitor screen 46; and a digital transceiver-type radio 48 connected to the computer and capable of transmitting a digital data stream. In the illustrative embodiment base reference receiver 16 is a high accuracy kinematic GPS receiver; computer 42 for example is a 486DX computer with a hard drive, 8 megabyte RAM, two serial communication ports, a printer port, an external monitor port, and an external keyboard port; monitor screen 46 is a passive matrix colour LCD; and radio 48 is a commercially available digital data transceiver.

Position module 50 comprises a matching kinematic GPS receiver 18, a matching computer 52 receiving input from receiver 18, kinematic GPS software 54 stored permanently or temporarily in computer 52, a standard computer monitor screen 56, and a matching transceiver-type digital radio 58 which receives signals from radio 48 in base reference module 40. In the illustrative embodiment position module 50 is located on a compacting machine to move with it over the work site.

Update/control module 60, also carried on board the compacting machine in the illustrated embodiment, includes an additional computer 62 receiving input from position module 50; one or more site models 64 digitally stored or loaded into the computer memory; a dynamic database update module 66, also stored or loaded into the memory of computer 62; and a colour operator display screen 22 connected to

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the computer. Instead of, or in addition to, operator display 22, automatic machine controls 69 can be connected to the computer to receive signals which operate the machine in an automatic or semi-automatic manner in known fashion.

5 In Figure 4 module 60 further includes a transceiver-type digital radio 68, for example a low level spread spectrum radio, communicating with database computer 62 to supply it with position information received in broadcasts from other machines (not shown). Radio 68 is also capable of transmitting the position information from its own machine position module 50, received through computer 62, to the other machines.

10 15 Although update/control module 60 is here shown mounted on the geography-altering machine, some or all portions may be stationed remotely. For example, computer 62, site model(s) 64, and dynamic database 66 and radio 68 could be connected by radio data link to position module 50 and operator display 22 or machine control interface 69. Position and site update information can then be broadcast to and from the machine for display or use by operators or supervisors both on and off the machine.

20 25 Base reference station 40 is fixed at a point of known three-dimensional coordinates relative to the work site. Through receiver 16 base reference station 40 receives position information from a GPS satellite constellation, using the reference GPS software 44 to derive an instantaneous error quantity or correction factor in known manner. This correction factor is broadcast from base station 40 to position station 50 on the compacting machine via radio link 48,58. Alternatively, raw data can be transmitted

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from base station 40 to position station 50 via radio link 48,58, and processed by computer 52.

Machine-mounted receiver 18 receives position information from the satellite constellation, 5 while the kinematic GPS software 54 combines the signal from receiver 18 and the correction factor from base reference 40 to determine the position of receiver 18 and the geography-altering machine relative to base reference 40 and the work site within 10 a few centimetres. This position information is three-dimensional (e.g., easting, nording and elevation) and is available on a point-by-point basis according to the sampling rate of the GPS system.

Referring to update/control module 60, once 15 the digitized plans or models of the site have been loaded into computer 62, dynamic database 66 generates signals representative of the difference between the actual and desired site models to display this difference graphically on operator display screen 22 relative to the site topography. Using the position 20 information received from position module 50, the database 66 also generates a graphic icon of the geography-altering machine superimposed on the site topography on display 22 corresponding to the actual 25 position and direction of the machine on the site.

Because the sampling rate of the position module 50 results in a time/distance delay between position coordinate points as the compacting machine moves over the site, the dynamic database 66 of the 30 present invention uses a differencing algorithm to determine and update in real-time the path of the machine.

With the knowledge of the geography-altering machine's exact position relative to the site, the 35 difference between the actual and desired site models,

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and the machine's progress relative thereto, the operator can maneuver the compacting machine over the site to alter it without having to rely on intuitive feel, memory or physical site markers. And, as the 5 operator moves the machine over the site the dynamic database 66 continues to read and manipulate incoming position information from module 50 to dynamically update both the machine's position relative to the site, the path of the machine over the site, and any 10 change to the site (e.g., topography, degree of compaction) affected by the machine's passage. This updated information is used to generate representations of the site and can be used to direct the operation of the geography-altering machine in 15 real time to bring the actual, updated site model into conformity with the desired site model.

To coordinate the operations of multiple machines on the site with a common, dynamically-updated database, database radio 68 receives position information from other machines on the site which are provided with their own position 20 modules 50 and their own counterparts to radio 68 for broadcasting their position information. Database computer 62 accordingly receives position information 25 from every machine on the site so equipped. Dynamic database 66 is updated in real time with the position of every machine relative to the site, the path of every machine over the site, and any change in the site effected or determined by each machine. The 30 operator is then provided with a display at 22 showing the position and work progress of each machine, and can coordinate their activities accordingly.

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Industrial Applicability

Referring to Figure 4A, an illustrative application of the invention is shown schematically in which three compacting machines 14, each provided with 5 a position module 50 and control module 60 as shown in Figure 4, are operating on a common site. The position module 50 on each machine determines that machine's position using reference signals from base reference module 40 and a GPS satellite constellation. 10 The position information from each module 50 on each machine is delivered to its control module 60 for dynamic updating of the site database. Additionally, a combined position/ID signal from the digital radio 68 associated with each control module 60 is 15 transmitted to a matching radio 68 on the other machines, such that the dynamic database on each machine is provided with position information corresponding to every machine on the site. The operator of each machine accordingly knows the exact 20 position of both his own machine and the other machines, and can adjust his operations accordingly. In this manner each machine effectively shares a common, dynamically-updated database, since each database is updated with the same position information 25 in a nearly simultaneous fashion.

Referring now to Figure 5 a method for transmitting the position information between machines is illustrated. Digital radio 68 in the illustrated embodiment is a low power spread spectrum radio 30 capable of making a general broadcast of a combined position/ID signal to the other machines on the site. To prevent interference between the position/ID signals from the different machines as they are received and processed by the dynamic database, each 35 digital radio 68 is assigned a time slot in which to

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broadcast its signal, such that one machine broadcasts while all others receive. In the illustrated embodiment the time slots are synchronized with the GPS sampling rate of one coordinate point per second.

5       In the schematic chart of Figure 5, the one second time interval between a first GPS sample coordinate  $t_0$  ( $x_0$ ,  $y_0$ ,  $z_0$ ) and a second GPS sample coordinate  $t_1$  ( $x_1$ ,  $y_1$ ,  $z_1$ ) is divided into N broadcast time slots 68a - 68n (in practice, one corresponding  
10      to each compacting machine 14 illustrated in Figure 4A). At time slot 68a a first machine transmits its position information from sample coordinate time  $t_0$  to the other machines; at broadcast time slot 68b a second machine transmits its position information determined at sample coordinate  $t_0$ ; at broadcast time slot 68c the third machine transmits its position information at sample coordinate time  $t_0$  while the other two receive, and so on. In this fashion machine position/ID signals can be traded in the interval  
15      between GPS coordinate samples without interference and in a manner enabling database computer 62 to update the site database one machine at a time. The number of machines which can share information to generate a common, dynamically-updated site database  
20      is accordingly limited only by the speed at which position information can be determined in module 50, transmitted by radio 68, and processed by computer 62.  
25

It will be understood that the invention is not limited to a spread spectrum radio or any particular data transmission link. Virtually any wireless broadcast and receiver system can be used to share the machine position information necessary to generate a common site database for several machines.

Referring now to Figures 6 and 7A-7I, a

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further application of the present invention is illustrated for a landfill compacting operation.

In machine compacting, for example of landfills, earth, or freshly laid asphalt, the completion of the compacting operation is typically a function of the number of passes of the compactor over the surface to be compacted. The desired degree of compaction can be determined, for example, by running a compactor over a test area of uncompacted material and empirically determining a suitable pass-count standard. By way of illustrative example, in a landfill compacting operation it is desirable that a machine such as a large, heavy compactor with studded rollers or wheels pass over a portion of the landfill to compress new refuse to some predetermined degree in accordance with local compaction regulations or sound compacting practices. It is therefore important for the operator of the compactor to know: whether he has been over a given unit area or grid element of the landfill site; how many times the compactor has been over a given grid element on the site; the extent to which the material has been successfully compacted within a grid element on the site; and, whether uncompacted material has been added to a particular grid element since the last compacting pass.

Systems and software are currently available to produce digitized, two- or three-dimensional maps of a geographic or topographic site. For example, a topographic blueprint can be converted into a three-dimensional digitized model of the initially surveyed topography as shown at 36 in Figure 6A and of a subsequent site topography, for example after a landfill has been filled in or the original site contour is altered, as shown at 38 in Figure 6B. The site contours can be overlaid with a reference grid of

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uniform grid elements 37 in known fashion. Digitized site plans can be superimposed, viewed in two or three dimensions from various angles (e.g., plan or profile), and colour coded to designate areas in which 5 the site needs to be altered from the actual state to the desired state.

At the start of the compacting operation, the actual site model may initially comprise a three-dimensional survey or map of the site topography 10 in an uncompacted state, for example a digitized three-dimensional site model as shown in Figure 6A. As compacting operations progress, the actual site model more specifically comprises the actual degree of compaction of the material on the surface of the site, 15 as measured for example by compaction pass count and/or elevation change. The actual site model is dynamic in that it changes each time new material is added or old material is further compacted from its previous state.

20 The desired site model comprises a predetermined, desired degree of compaction for material on the surface of the site. For example, where the desired degree of compaction is predetermined to be a total of five passes of the 25 compactor over a previously uncompacted area, the desired site model is a pass count of five passes over a previously uncompacted area. When that pass count is reached, the desired site model is achieved. The difference between the actual and desired site models 30 at any point on the site comprises the difference between the actual degree of compaction and the desired degree of compaction at that point.

The actual site model accordingly fluctuates 35 between an uncompacted state of the site material and the desired degree of compaction. Whenever new,

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uncompacted material is detected in a previously compacted area of the site, the actual site model returns or decrements to an uncompacted state for that area.

5           Using the method and apparatus of the present invention, all of this information previously available for a single machine can be determined and updated in real time for multiple machines to generate a common, dynamically updated database.

10           Figure 6 shows a sample operator display 22 for a compacting operation according to the present invention. Using a digitized model of the landfill site with a superimposed set of grid elements, and two compactors equipped with position modules 50 and update/control modules 60 as in Figures 4 and 4A, the operator first initializes the operator display 22, typically upon entering the landfill site. In landfill compacting the probable activity field for a day is typically small, on the order of a few hundred 15 or thousand square metres. For purposes of illustration in Figure 6 the site database is arbitrarily set at approximately 30 metres by 40 metres. This can be varied depending on the nature of the particular compacting operation. This is smaller than the total area of a typical landfill, but for a 20 single day the compactor operators need a database only for the portion of the landfill in which they will be operating.

25           In the illustrated embodiment the site is divided into a grid of square elements of fixed area, e.g., one square metre.

30           The operators initialize their displays and are presented on their respective screens 22 with a site database in plan window 70 such as that shown in Figure 6, marked off in a grid pattern of elements 71

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initially all one colour; e.g., black to indicate that no passes have yet been made over that site. A position coordinate window 72 displays the associated compactor's current position in latitude, longitude, 5 elevation and time. A window 73 displays a colour key for the compaction status of grid elements 71 displayed and updated in plan window 70; in Figure 6 the various colours or shadings represent a pass count. The position of each compactor is represented 10 by an icon 82,82' with direction indicator 84,84'.

With the exchange of position information between the position modules 60 on the compactors as described in Figures 4 and 4A above, the operator display 22 on each machine shows the real time 15 positions of each compactor relative to the site as illustrated in Figure 6.

As a further feature of the present invention, each compactor icon 82,82' on display screen 22 is provided with a peripheral spacing or boundary icon, in Figure 6 a boundary box 83, to maintain a safe margin between the machines as they operate on the site. For example, if the position or boundary icon 83 of one compactor should be determined 20 to touch or overlap that of another compactor on screen 22, the database provides a warning to the operators, for example a visual or audible signal via an indicator or buzzer/beeper associated with screen 22 shown schematically in Figure 6 at 85. The machine operators can then adjust their operations to avoid 25 work interference or collision.

The size of boundary box 83 for each machine 30 can be varied relative to the machine depending on the machine's mode of operation. For example, where the machine is operating in a slower mode with a correspondingly greater amount of time to correct for

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potential interference between machines, the boundary defined around the machine is set at a first smaller size. When the machine operates in a faster mode, the boundary can be set at a correspondingly greater size 5 to allow sufficient reaction time once a warning is given. Alternately, multiple layers of boundaries 83 can be employed, each generating a successively more urgent warning as they are violated by the position or boundary of another machine. It will be understood by 10 those skilled in the art that operating parameters other than machine speed can be used as the basis for determining and setting an appropriate boundary around each machine monitored in this fashion.

Each compactor icon 82, 82' on screen 22 is 15 visually distinct so that the operator knows which represents his own machine, and which represents the other machine or machines. Although in the illustrated embodiment of Figure 6 the difference is shown by cross-hatching, on an actual display 20 different colours can be used. For different types of machines other visual distinctions are possible, for example different shapes or outlines.

Prior to the beginning of work on the site, a compaction standard (here a pass count) is set to 25 denote the desired degree of compaction of the site. For example, it may be determined that five passes of the compactor over uncompacted material on any one grid element are necessary for that grid element to be adequately compacted. As the compactors traverse the 30 site, each pass of the compactor wheels over a grid element will result in a database update in real-time. The grid elements of the site display can be visually updated in a variety of ways to show the difference 35 between the actual and desired degree of compaction, e.g., shading, cross-hatching, colouring or "painting"

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(where a colour display is used), or in any other known manner to provide an indicator to the operators of the compaction status of the grid elements. In the illustrated embodiment of Figure 6, using a colour monitor, the grid changes colour to denote the actual degree of compaction in terms of how many passes have been made; e.g., the darkest to lightest shading of grid elements 71 represent black for no passes, yellow for one pass, green for two passes, red for three passes, blue for four passes, and white indicating satisfactory compaction at five passes. The objective is to make the entire screen white as the operator display is updated in real-time to indicate the number of passes over each grid element.

Since the dynamically updated database of the present invention is provided with real time position information for both compacting machines 82, 82', the site model in the site database is updated with the topography or compaction changes effected by each machine. As shown in Figure 6, the operator accordingly has real time information on the position of each machine operating on the site, and the collective site update information indicating the total work of the machines on the site. Operators can accordingly avoid machine interference or unnecessary overlap of work on the site. Or, they can more effectively coordinate their efforts in altering the site from the actual state to the desired state.

As an additional aid to the machine operators, the approximate paths of the compactor as measured by coordinate samples can be shown on display 22, in Figure 6 denoted by a series of dots 86 where each position reading was taken.

It is necessary to provide some protocol for determining when a sufficient portion of a grid

element has been passed over by a compactor wheel to warrant a status update for that grid element and register a compacting pass on the operator display.

For the illustrated compactors with two or more spaced compacting wheels, the following illustrative method can be used. The size of each grid element on the digitized site plan is preferably matched to the width of a compacting wheel; e.g., for one metre wide wheels the grid elements should be set to one square metre.

Accordingly, if the centre of the wheel crosses a grid element at any point, it is assumed that at least one half of the grid element has been compacted and can be updated on the display. These dimensions and margins can be varied as desired, however.

The coordinates of the ground-contacting surfaces ("footprints") of the fixed rear compactor wheels are known relative to the position receiver on the compactor. Each coordinate sampling by the positioning system can accordingly be used to determine the precise location of the centre of each wheel at that point. In the illustrated embodiment the positions of the footprints of the rear compactor wheels are tracked.

For site operations other than compacting, it will be understood that the position of virtually any portion of the geography-altering machine can be determined relative to the position receiver on the machine, such that each coordinate sampling by the positioning system can be used to determine the precise location of that portion of the machine. For example, in an earth-contouring operation using a tractor equipped with a dozer blade, the position of the tracks or the blade can be determined based on their position relative to the position receiver on the tractor. If possible, it is desirable to place

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the position receiver close to or on the operative portion of the machine. In a compacting operation the position receiver(s) might preferably be located directly over one or more of the compacting wheels.

5      For earth contouring with a blade-equipped tractor, the position receiver can be mounted directly on the blade. If the portion of the machine being tracked via the position receiver is one which is not always in contact with the site, it may be desirable to

10     provide a sensor of known type on the operative portion to indicate when it is contacting the site surface and actually altering the geography/topography.

In the illustrated compacting embodiment, the time lag between coordinate samplings as the compactor wheels travel over several grid elements must also be taken into consideration to accurately determine the entire real-time path of each compactor. In a compactor with compacting wheels whose width approximates the width of the site model grid elements, a preferred method shown in the illustrated embodiment of the present invention uses the well-known Bresenham's algorithm to produce a continuous line approximating the path of each compactor wheel over the grid elements between coordinate samplings. Then, if the sampling rate only provides a coordinate "point" every three or four grid elements, a line approximation is made of the compactor wheel paths over those three or four grid elements (corresponding to the centre of the wheels), and every grid element along that line is given a status update and visual change on the operator display.

15     20     25     30     35

Other techniques for measuring the paths of the machines as they traverse the site are known and

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may be used, depending on the characteristics of the machines, the work, and/or the site. For the illustrative landfill compacting example, the Bresenham's line approximation of the wheel paths is  
5 useful.

Referring now to Figures 7A-7I, particularly 7A and 7H-7I, the method of the present invention as applied to a landfill compacting application is schematically shown for receiving position information  
10 from at least two machines to create a dynamically updated common database. At step 500 in Figure 7A the operator starts from the computer operating system. At step 502 database memory is allocated and initialized. At step 503 operating parameters for  
15 each machine which affect the manner in which their paths or progress is tracked by the database algorithms are initialized, for example in a machine parameter library. At step 504 the various displays are initialized. In step 506 the serial  
20 communications between the site database and positioning modules 50 on first and second compactors are initialized.

For purposes of illustration it will be assumed that one serial port is from a first or "home" compactor on which a position module 50 and control module 60 are located as shown in Figure 4, while the second serial port delivers position information received by a database radio 68 from another machine's position module 50 broadcast via digital radio link as  
25 described above. However, it will be readily understood that the method illustrated in Figures 7A-7I is suitable for a fixed, off-machine database receiving both position inputs by wireless broadcast.

At step 508 the system determines whether  
35 there has been an operator request to terminate the

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program, for example from a user interface device such as a computer keyboard. This option is available to the operator at any time, and if the system determines that such a request to terminate has been received, it 5 proceeds to step 592 and stores the current site database in a file on a suitable memory device, for example a disk. At steps 594,596 the operator is returned to the computer operating system.

If, however, the system determines at step 10 508 that there has not been a request to terminate the program, it proceeds to step 510 where a position coordinate is read from the first serial port connection between the first compactor's position module 50 and update/control module 60 of Figure 4, in 15 the illustrated embodiment a three-dimensional GPS-determined coordinate point. At step 511 a second position coordinate is read from the second serial port connection delivering the position information from other compactors' timed broadcast. At step 512 20 the position of the first or "home" compactor 14 is displayed (Figure 6) in window 72 on operator display screen 22 as three-dimensional coordinates relative to base reference 16.

In steps 514,515 a subroutine shown in 25 Figures 7B-7C draws the display and icons based on the position information from each compactor. The subroutine determines the orientation of the compactor and the position of the centres of the "footprints" or ground-contacting portions of the rear compactor 30 wheels, tracks the path of the rear compactor wheels over the site database, and updates the compaction status of the grid elements in the path of the compactor. The subroutine runs successively for each compactor in the order its position information is 35 received at steps 510,511.

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Referring to Figure 7B, at step 516 the system determines whether the first program loop has been executed. If not, the site database and display window coordinate systems are initialized and displayed on operator screen 22 at step 518. After the first program loop has been executed and the site database initialized and displayed on the operator screen, the system at step 520 checks whether the appropriate icon 82 or 82' has already been drawn. If yes, that icon is erased from the display at step 522. If the icon for that compactor has not yet been drawn, at step 524 the system determines whether the first loop has been executed; if not, the orientation of the compactor is initialized at step 526 and the system completes the overall program loop of Figure 7A. If at step 524 the system determines that the first loop has already been executed, the system proceeds in Figure 7B to step 528 to determine whether the compactor has moved since the last program loop. If the machine has not moved, the system exits the subroutine of Figure 7B and returns to complete the overall program loop of Figure 7A from step 514.

If the machine has moved relative to the site database since the last loop, the system proceeds to step 530 in Figure 7B to calculate the positions of the centres of the footprints of the rear compactor wheels, and from those the orientation of the compactor. At step 532 in Figure 7C the system determines whether the right rear compactor wheel position has moved out of the grid element it occupied during the last position measurement. If it has, at step 534 the path of the right wheel between the previous and current coordinate samplings is determined using the well-known Bresenham's algorithm to approximate a continuous line path of the right

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wheel over the grid elements on the display 22. The grid elements of the site database over which the right wheel has passed are then updated to indicate a compaction pass, and grid elements are updated on the 5 visual display window 70 with a colour change or other visual indicator.

If at step 532 the right wheel has not moved since the last position measurement, or after the movement of the right wheel has been tracked and the 10 site database updated at step 534, the process is repeated for the left wheel of the compactor at steps 536,538. At step 591 the updated compactor icon is then redrawn on the display to show its current position and direction. The subroutine of step 514 in 15 Figure 7A is then completed for the first compactor. If position information has been received from the second compactor, the subroutine illustrated in Figures 7B and 7C is repeated for the second compactor at step 515.

When steps 514,515 have been completed for each compactor the system proceeds to step 515a where the interaction between machines on the site is monitored, and appropriate warning given if operating safety margins are exceeded, according to a subroutine 20 described below in Figure 7I. The system then returns to repeat the program loop of Figure 7A, either 25 proceeding to step 510 for more GPS coordinate samplings, or terminating in response to an operator request.

In Figure 7D a subroutine for the wheel tracking and site updating operations of steps 534 and 30 538 is shown. At step 540 the starting and ending grid cells for the wheel whose path is being determined are defined by the current wheel position 35 measurement and the previous wheel position

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measurement taken by the GPS or other positioning system. The Bresenham's algorithm is applied to determine the grid cells located along the path between the starting and ending grid cells, and the 5 system proceeds to steps 544,546,548 to evaluate/update the status of each grid element therebetween, beginning with the first grid element after the starting grid element. At step 542 the system determines whether the ending grid element has 10 been evaluated; if not, it proceeds to step 544 where the grid element being evaluated is updated according to a subroutine in Figure 7G. Once the compaction status of the current grid element has been updated at step 544, the updated grid element is displayed on the 15 operator screen 22 at step 546, and at step 548 the system is incremented to evaluate the next grid element in the path between the starting and ending grid elements. This loop repeats itself until the ending grid element has been evaluated and updated, at 20 which point the subroutine of Figure 7D is exited and the program returns to step 591 in Figure 7C to draw the updated compactor icon on the display.

In Figure 7H a subroutine for the 25 icon-drawing step 591 in Figure 7C is illustrated for coordinating the display of multiple machines on the operator display screen. At step 591a the system matches the mixed position/ID signal from the machine whose position is currently being evaluated to a set of corresponding machine parameters from an accessible 30 library. The ID for each machine is preferably stored in the database on each machine, such that the common database effectively has each machine "tagged" for identification. When a match is found, the icon size and orientation are calculated in the 35 three-dimensional coordinates of the display 70. At

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step 591b the system determines whether the coordinates match those of icon 82 representing the first or "home" compactor. If yes, the system is set to colour that icon in the appropriate manner, for example by painting it green, at step 591d. If at step 591b the display window coordinates calculated for the current icon are determined not to represent the first compactor icon 82, the system is set to visually distinguish the current icon, for example by colouring it red at step 591c. At step 591e the icon is then drawn on the plan window with the appropriate colour or other visual characteristic distinguishing it from the other icon(s) on the display.

Still referring to Figure 7H, at step 591f the icon currently being evaluated is provided with a boundary box 83 as described above, for example in the illustrated embodiment representing one metre of clearance around the machine. The subroutine of Figure 7H is repeated for each compactor at step 591 as the system successively evaluates each machine operating on the site. It will be apparent that the subroutine of Figure 7H is easily expanded to accommodate more than the two illustrative machines.

Referring now to Figure 7I, a subroutine for step 515a in Figure 7A is illustrated for monitoring a safety margin or interference boundary around each compactor. At step 515b the limits of the currently evaluated or "home" machine boundary box 83 are defined, for example to provide one metre of clearance around the machine. At step 515c the system determines whether the box of the other machine(s) interferes with the box of the primary machine as defined in step 515b. If yes, the operator is alerted at step 515d, for example with a flashing light and/or audible warning signal such as a beep or buzzer

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indicating the need for corrective action. If at step 515c the boxes of the two machines are determined not to interfere with one another, the subroutine proceeds to step 515c to determine whether the other machines 5 on the site have been evaluated for interference with the home machine. If no, the next machine on the site is checked at step 515f and the subroutine is repeated. If all machines on the site have been checked, the subroutine terminates and the system 10 returns to step 515a in Figure 7A. In this manner the system checks for interference between each machine operating on the site in the interval between position samplings. The risk of collision or interference 15 between machine operations is accordingly reduced or eliminated.

In Figure 7E the subroutine for the site database update step 544 of Figure 7D is shown. Referring to Figure 7E, at step 550 the system determines whether the elevation of the current grid 20 element has been initialized. If not, the elevation or z-axis coordinate of that grid element is initialized as equal to the currently measured compactor wheel elevation at that point. If the grid element elevation has already been initialized, the 25 system proceeds to step 554 to compare the currently measured wheel elevation to the previously measured elevation for that grid element. If the currently measured wheel elevation on that grid element is not greater than the previously measured elevation, the 30 system determines that no new material has been added and that grid element can be incremented at step 558 to register a compaction pass and increment the pass count for that grid element. If at step 554 the 35 currently measured wheel elevation is greater than the previously measured elevation (discounting, for

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example, minor resilient expansion of the material compressed in the last pass, within limits determined by the user) the system determines at step 556 that a new lift of asphalt, earth or waste material has been detected for that grid element, and the pass count status for that grid element is re-zeroed to indicate the need for a complete new series of compaction passes. At step 560 the elevation of the current grid element is then set equal to the currently measured elevation of the compactor wheel for comparison at step 554 on the next pass of the compactor over that grid element. The subroutine of Figure 7E is then exited for completion of the subroutine loop of Figure 7D.

Referring now to Figures 7F-7G, a subroutine for step 546 of Figure 7D is shown. Once the pass count for the current grid element has been updated at step 544 in Figure 7D using the subroutine of Figure 7E, the system in step 546 enters the subroutine of Figures 7F-7G and at step 562 first determines the location and size of the current grid element for that compactor on the site database displayed in plan window 70 on the operator screen 22. At step 564, if the pass count for the grid element is zero, the grid element is set, for example, to be coloured black on the display at step 566. If the pass count for that grid element is determined to be one at step 568, the grid element is set, for example, to be coloured yellow on the display at step 570. If the pass count for that grid element is determined at step 572 to be two, the grid element is set, for example, to be coloured green at step 574. If the pass count is determined at step 576 to be three, the grid element is set, for example, to be coloured red at step 578. If the pass count for that grid element is determined

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at step 580 to be four, the grid element is set, for example, to be coloured blue at step 582. If the pass count is determined at step 584 to be five (in the illustrated embodiment the desired pass count for a completed compacting operation), the grid is set, for example, to be coloured white at step 586. If the pass count for that area is greater than the minimum pass count for a completed compaction operation, the grid element is set to be coloured white at step 588.

Once the grid element has been updated according to the current pass count, the grid element is drawn and coloured on the operator display screen 22 at step 590. It will be understood that the grid elements can be visually updated on screen 22 other than by colouring; e.g., by cross-hatching, shading or other visual indication.

While the tracking and updating method of Figures 7A-7I are illustrated for a compactor having two or more spaced compacting wheels whose width approximates the width of the site grid elements, the method can also be used for a compactor with a single wheel or roller as will be understood by those skilled in the art. The method of Figures 7A-7I can also be used where the width of the compactor wheel or roller does not match the width of the grid elements of the site model. However, where the width of the compacting wheel or roller is significantly greater than the width of a single grid element, for example where it covers several grid elements at one time, an alternate method for tracking the path of a compacting wheel or roller may be employed.

This is accomplished by replacing step 530 in Figure 7B with step 530' from Figure 7J, and the subroutine of Figure 7D with the subroutine of Figure 7K. Referring to step 530' in Figure 7J, the system

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designates "effective" wheel or roller ends inboard from the actual ends. In the illustrated embodiment the effective ends are recognized by a differencing algorithm as inboard from the actual end a distance approximately one half the width of a grid element.

5 For example, if the actual wheel width is 1.5 m (5.0 feet), corresponding to five 0.3m (1.0 foot) x 0.3m (1.0 foot) grid elements, the effective locations of the wheel ends can be calculated, for example, 0.15m (½ft) inboard from each actual end. If the effective (non-actual) wheel ends of the compactor pass over any portion of a grid element on the digitized site model, that grid element is read and manipulated by the differencing algorithm as having been compacted, since

10 in actuality at least one half of that grid element was actually passed over by the wheel. Of course, the amount of wheel end offset can vary depending on the size of the grid elements and the desired margin of error in determining whether the wheel has passed over

15 a grid element.

20

While the algorithm of step 530' in Figure 7J compensates for the lack of complete correspondence between the width of the compacting wheel or roller and the number of grid elements completely traversed by the wheel or roller, the distance and direction changes which the wheel makes between GPS position readings results in a loss of real time update information over a portion of the compactor's travel. This is particularly acute where compactor travel

25 speed is high relative to the grid elements of the site plan. For example, where the grid elements are one metre square and the sampling rate of the position system is one coordinate sample per second, a machine travelling at 18 km per hour travels approximately

30 five metres or five grid squares between position

35

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samplings. Accordingly, there is no real time information with respect to at least the intermediate three of the five grid squares covered by the machine. To solve this problem a "fill in the polygon" 5 algorithm as shown in Figure 7K is used to estimate the path traversed by the machine between coordinate samplings. In Figure 7K the algorithm at step 540' locates a rectangle on the site plan grid surface defined by the effective ends of the compactor wheel 10 at positions  $(x_1, y_1)$  and  $(x_2, y_2)$  and coordinate position  $(x_0, y_0)$ . At steps 542', 543' and 548' a search algorithm searches within the rectangle's borders for those grid elements within a polygon 15 defined between the two wheel positions; i.e., those grid elements traversed by the wheel between its effective ends.

The machine path tracking method of Figures 7J and 7K is also useful for tracking earth-contouring machinery, for example a tractor having a dozer blade, 20 by substituting the width of the blade or tool on the earth-contouring machine for wheel/roller width in step 530'.

At steps 544' and 546' the database and display are updated as described at steps 544 and 546, 25 respectively, in Figures 7D-7F.

While the illustrated embodiment of a compacting application is a pass-count based system, it will be apparent that other update protocols can be employed. For example, the change in amount of 30 compaction per pass over a grid element can be determined by checking the elevation change since the last pass, and when the change in elevation on a particular pass is below a certain value (indicating that the garbage is near the desired compaction 35 density), that grid element is updated on the screen

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as completed. Another method is to use an absolute compaction standard, registering a particular grid element as finished when the material thereon has been compacted from an uncompacted or initial elevation to 5 a predetermined lower elevation.

It will be apparent to those skilled in the art that the principles of the present invention, i.e., multiple machine monitoring and coordination via the creation of a common, dynamically-updated site 10 database created with shared machine position information, is not limited in utility to the exemplary landfill compacting operation described above. The inventive method and apparatus can be applied to virtually any earth-moving, contouring or 15 compacting operation in which mobile geography-altering machinery using real time three-dimensional positioning and a dynamically updated site database are operating on a common site.

For example, referring to Figure 8 a display 20 screen can be generated for an alternate application of the present invention in which multiple earth contouring machines such as tractors with dozer blades are operating on a site to contour the topography to a desired state. The method and apparatus for 25 generating a dynamically updated database for such machines is similar to the method and apparatus described above for a compacting machine; as noted above, the machine path tracking method of Figures 7J and 7K can be used for tracking earth contouring 30 machinery simply by substituting blade width for wheel/roller width. While the difference between the actual and desired site models in the illustrated compacting application is determined and displayed as an incremental pass count, for earth-contouring the 35 difference can be determined by comparing the

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machine's current elevation coordinate to the desired or target elevation at that point, and the site database updated at that point to indicate whether the actual topography is above, at, or below the target.

5       The sharing of position information to create a common, dynamically-updated database as described above for a particular compacting operation can be modified accordingly by those skilled in the art. With the general principles and a specific application  
10      of the present invention set forth above, those skilled in the art will be able to carry it out.

For example, referring to Figure 8 an operator display on screen 22 for an earth-contouring application can be generated by equipping two earth-contouring machines with the position and update modules 50,60 described above. The display has as a principal component a two-dimensional digitized site model in plan window 70 showing the desired final contour or plan of site 12 (or a portion thereof) relative to the actual topography. On an actual screen display 70 the difference between the actual site topography and the desired site model can be represented by colour coding used to show areas in which earth must be removed, areas in which earth must be added, and areas which have already achieved conformity with the finished site model. The differently shaded or cross-hatched regions on the site displayed in window 70 in Figure 8 graphically represent the varying differences between the actual site topography and desired site topography, updated in real time for each machine on the site.

Operator display screen 22 includes a horizontal coordinate window or display 72 at the top of the screen, showing the position of the "home" machine 82 in three dimensions relative to base

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reference 16. Coarse and fine resolution sidebar scales 74,75 show the elevational or z-axis deviation from the target contour elevation, providing an indicator of how much the tractor's blade should cut or fill at that location. The coarse indicator 74 on the right shows scaled elevation of 1.0 foot increments above and below the target elevation; the fine resolution side bar 75 of the left side of the display lists 0.1 foot increments and provides a convenient reference when the operator is within a foot or less of the target contour. Using "zoom" or "autoscaling" features in the display software, the scales 74,75 can be changed to smaller increments as the operator nears the target topography.

A further reference is provided to the machine operator in profile window 76 at the bottom of screen 22. Profile window 76 shows the elevational difference between the actual site topography 76a and the desired topography 76b in the path of and immediately behind the "home" machine. An elevation scale 78 on the left side of profile display 76 can provide an additional indicator of how deep to make a cut or how much earth to add at a given location, while the horizontal scale 79 at the bottom of profile display 76 indicates the distance ahead of the tractor/ blade at which the operator will encounter certain actual and desired topography differences. In this manner the operator can simultaneously monitor the upcoming terrain and the accuracy of the most recent pass in achieving the target contour, and adjust operations accordingly.

The position of two tractors on site 12 is displayed graphically on screen 22 as tractor blade icons 82,82' superimposed on the plan window 70. Only the "home" machine icon 82 appears in the profile

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window 76, and the appropriate sidebar scale 74,75. In the site plan window 70 icons 82,82' are provided with forward-projecting direction indicators 84,84', which serve to identify the terrain a fixed distance ahead of the tractors in their direction of travel. 5 The anticipated terrain shown in front of "home" tractor icon 82 in profile window 76 corresponds to that portion of site 12 covered by direction indicator 84. While icon 82 in windows 70,74,75 moves in 10 response to the current position of the machine relative to the site, the icon 82 in profile window 76 remains centred while the site topography profiles 76a,76b scroll past it according to machine movement.

With the detailed position and site update 15 information for both tractors 82,82' provided to the operator via display 22 the operator has a complete, up-to-date, real-time display of the entire site, both tractors and their progress to date, and their success in achieving the desired topography.

It will be understood by those skilled in 20 the art that the inventive method and apparatus illustrated in Figures 1-7 for compacting operations can be applied to multiple earth-contouring machines as shown in Figure 8, or indeed to any geography-altering machine, with minor variations for the 25 operating characteristics of the machinery and the manner in which the site is being altered to the desired state.

Referring now to Figure 9, an alternative 30 system is schematically shown for closed-loop automatic control of one or more operating systems on a machine. While the embodiment of Figure 9 is capable of use with or without a supplemental operator display as described above, for purposes of this 35 illustration only automatic machine controls are

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shown. A suitable digital processing facility, for example a computer as described in the foregoing embodiments, containing the algorithms of the dynamic database of the invention is shown at 400. The 5 dynamic database 400 receives 3-D instantaneous position information from GPS receiver system 410, and the shared position information from other machines via database radio 411. The desired site model 420 is loaded or stored in the database of computer 400 in 10 any suitable manner, for example on a suitable disk memory. Automatic machine control module 470 contains electrohydraulic machine controls 472 connected to operate, for example, steering and drive systems 474, 476, 478 on the compacting machine. Automatic 15 machine controls 472 are capable of receiving signals from the dynamic database in computer 400 representing the difference between the actual site model 430 and the desired site model 420 to operate the steering and drive systems of the compactor to traverse the site in 20 a manner to bring the actual site model into conformity with the desired site model. As the automatic machine controls 472 operate the steering and drive systems of the machine, the compaction of the site and the current position and direction of the 25 compactor are received, read and manipulated by the dynamic database at 400 to update the actual site model. The actual site update information is received by database 400, which correspondingly updates the signals delivered to machine controls 472 for 30 operation of the steering and drive systems of the compactor as it makes compacting passes over the site to bring the actual site model into conformity with the desired site model.

35 Additionally, the automatic machine controls 472 can be controlled by signals from the database to

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alter the machine's course in the event that interference with another machine is detected as described in Figure 7I.

The illustrated embodiments of the present invention are provided to further an understanding of the broad principles of the invention, and to disclose in detail a preferred application. Many other modifications or applications of the invention can be made and still lie within the scope of the appended claims.

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Claims

1. Apparatus (40,50,60) for monitoring and  
coordinating the operations of multiple mobile  
5 geography-altering machines (14) on a work site (12),  
the apparatus (40,50,60) comprising:

site database means (66,126) storing data  
representing a site model (64) of the geography of the  
site (12);

10 means (62,124) for generating signals  
representing the instantaneous three-dimensional  
coordinate position of the geography-altering machines  
(14) on the site (12);

15 means (62,124) for updating said site  
database means (66,126) in accordance with said  
signals; and

20 means (62,124) for providing control  
signals for transmission to said geography-altering  
machines (14) in response to updating of said site  
database means (66,126).

25 2. Apparatus (40,50,60) as defined in  
claim 1, further including a plurality of geography-  
altering machines (14).

30 3. Apparatus (40,50,60) as defined in  
claim 2, wherein the site database means (66,126) is  
located remotely from the machines (14).

35 4. Apparatus (40,50,60) as defined in  
claim 2, wherein the site database means (66,126) is  
located on one or more of the machines (14).

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5. Apparatus (40,50,60) as defined in  
claim 4, wherein each machine (14) provided with a  
site database means (66,126) further includes  
communication means (68,122) to send and receive the  
position signals to and from the site database means  
(66,126) on the other machine or machines (14).

10 6. Apparatus (40,50,60) as defined in  
claim 5, wherein the communication means (68,122)  
comprise asynchronous broadcasting means (68a,68b,68c)  
timed such that only one machine (14) per unit time  
broadcasts its position signal to the other machine  
(14).

15 7. Apparatus (40,50,60) as defined in  
claim 1 or claim 2, wherein the means (68,122) for  
generating position-representative signals includes  
means (68a,68b,68c) for asynchronously broadcasting  
the position signals from each machine (14) to the  
means (62,124) for updating the site database means  
(16).

20 25 8. Apparatus (40,50,60) as defined in  
claim 7, wherein the broadcasting means (68,122)  
further include ID signal means (68a,68b,68c) to  
broadcast a machine-identification signal with the  
position signal.

30 9. Apparatus (40,50,60) as defined in  
claim 8, wherein the means (62,124) for updating the  
site database means (66,126) further includes machine  
parameter library means (126) to match machine  
parameters to the ID signal from a machine (14).

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10. Apparatus (40,50,60) as defined in any of claims 1 to 9, further including means (60) for directing the operation of the machine comprising operator display means (22).

5

11. Apparatus (40,50,60) as defined in claim 10, wherein the operator display means (22) include a display of the site model (64) and the position of the machines (14) on the site model (64).

10

12. Apparatus (40,50,60) as defined in claim 10 or claim 11, wherein the operator display means (22) is located on one of the machines (14).

15

13. Apparatus (40,50,60) as defined in claim 10 or claim 11, wherein the operator display means (22) is located remotely from the machines (14).

20

14. Apparatus (40,50,60) as defined in any of claims 1 to 13, further including means (22) for monitoring the operation of the machines (14) relative to one another to prevent interference between them.

25

15. Apparatus (40,50,60) as defined in claim 14, wherein the means (22) for monitoring the operation of the machines (14) includes means (83,83') for defining a machine interference boundary around a machine (14) and providing a warning signal (85) in response to the position of another machine (14) being determined to be within that boundary.

30

16. Apparatus (40,50,60) as defined in claim 14, wherein the means (22) for monitoring the operation of the machines (14) include means (83,83') for defining a machine interference boundary around

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each of the machines (14) and providing a warning signal (85) in response to the boundary of one machine (14) being determined to overlap the boundary of another machine (14).

5

17. Apparatus (40,50,60) as defined in claim 16, further including means (62,124) for altering the size of the interference boundary (83,83') for a machine (14) in accordance with the 10 machine's mode of operation.

18. Apparatus (40,50,60) as defined in claim 16, wherein further comprising multiple boundaries (83,83') of different size simultaneously defined around a machine (14). 15

19. Apparatus (40,50,60) as defined in claim 10 and any of claims 15 to 18, wherein the operator display (22) of the site model (64) shows the 20 respective interference boundaries (83,83').

20. Apparatus (40,50,60) as defined in claim 2 or any claim dependent thereon, comprising:  
means (68,122) on each machine (14) for 25 transmitting that machine's position signals to another machine (14), and for receiving position signals from another machine (14).

21. A method (100,101,102,104,106,108, 30 108a,109,110) of monitoring and coordinating the operations of multiple mobile geography-altering machines (14) on a work site (12), the method comprising:

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maintaining a site database (66) containing data representing a site model (104,106) of the geography of the site (12);

5 generating signals representing the instantaneous three-dimensional coordinate position of the geography-altering machines (14) on the site (12);

receiving said signals and updating said site database means (66) in accordance with said signals; and

10 providing control signals for transmission to said geography-altering machines (14) in response to updating of said site database means (66).

22. A method (100,101,102,104,106,108, 15 108a,109,110) according to claim 21, further comprising:

directing the operation of the machines (14) in accordance with the site database (66).

20 23. The method (100,101,102,104,106,108, 108a,109,110) as defined in claim 21 or claim 22, wherein the site database means (66) is located on each of the machines (14) and further including the step of sharing the position signals of each machine (14) with the site database means (66) on each machine (14), and updating the site database (66) on each machine (14) in accordance with the position signals from each machine (14).

30 24. The method (100,101,102,104,106,108, 108a,109,110) as defined in claim 23, further including the step of asynchronously broadcasting the position signals of each machine (14) such that only one machine (14) per unit time broadcasts its position

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signal to the site database (66) on another machine (14).

25. The method (100,101,102,104,106,108,  
5 108a,109,110) as defined in claim 24, further  
including the step of storing the machine-identifying  
signal in the site database (66) on each machine (14),  
broadcasting the machine-identifying signal with the  
position signal, and matching the position/ID signal  
10 from each machine (14) with machine parameters and  
updating the site database (66) in accordance  
therewith.

15 26. The method (100,101,102,104,106,108,  
108a,109,110) as defined in any of claims 21 to 25,  
including the step of asynchronously broadcasting the  
position signals from each machine (14) to the site  
database (66).

20 27. The method (100,101,102,104,106,108,  
108a,109,110) as defined in any of claims 24 to 26,  
further including the step of broadcasting a machine-  
identifying signal with the position signal.

25 28. The method (100,101,102,104,106,108,  
108a,109,110) as defined in claim 27, further  
including the step of matching the position/ID signal  
from a machine (14) with machine parameters and  
updating the site database (66) in accordance  
30 therewith.

35 29. The method (100,101,102,104,106,108,  
108a,109,110) as defined in any of claims 21 to 28,  
wherein the step of directing the operation of the  
first machine (14) relative to the second machine (14)

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includes the step of providing a display (22) of the site database.

30. The method (100,101,102,104,106,108,  
5 108a,109,110) as defined in claim 29, wherein the operator display (22) includes a display of the site model (64) and the position of the machines (14) on the site model (64).

10 31. The method (100,101,102,104,106,108,  
108a,109,110) as defined in claim 22, wherein the step of directing the operation of the machines (14) includes the step of providing real time control signals to automatic machine controls on the machines  
15 (14).

32. The method (100,101,102,104,106,108,  
20 108a,109,110) as defined in any of claims 21 to 31, further including the step of monitoring the operation of the machines (14) relative to one another and providing a warning (85) to prevent interference between them.

25 33. The method (100,101,102,104,106,108,  
108a,109,110) as defined in claim 32, wherein the step of monitoring the operation of the machines (14) further includes the step of defining a machine interference boundary (83,83') around a machine (14) and providing a warning signal (85) when the position  
30 of another machine (14) is determined to be within that boundary (83,83').

35 34. The method (100,101,102,104,106,108,  
108a,109,110) as defined in claim 32, wherein the step of monitoring the operation of the machines (14)

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further includes the step of defining a machine interference boundary (83,83') around each of the machines (14) and providing a warning signal (85) when the boundary (83) of one machine (14) is determined to  
5 overlap the boundary (83') of the other machine (14).

35. The method (100,101,102,104,106,108,  
108a,109,110) as defined in claim 34, further  
including the step of altering the size of the  
10 interference boundary (83,83') for a machine (14) in  
accordance with the machine's mode of operation.

36. The method (100,101,102,104,106,108,  
108a,109,110) as defined in claim 34, further  
15 comprising defining multiple boundaries (83,83') of  
different size simultaneously defined around a machine  
(14).

37. The method (100,101,102,104,106,108,  
20 108a,109,110) as defined in claim 29 and claims 35 or  
36, which includes the step of displaying on the  
display (22) of the site model (64) the position of  
the first and second machines (14) on the site model  
(64) and their respective interference boundaries  
25 (83,83').

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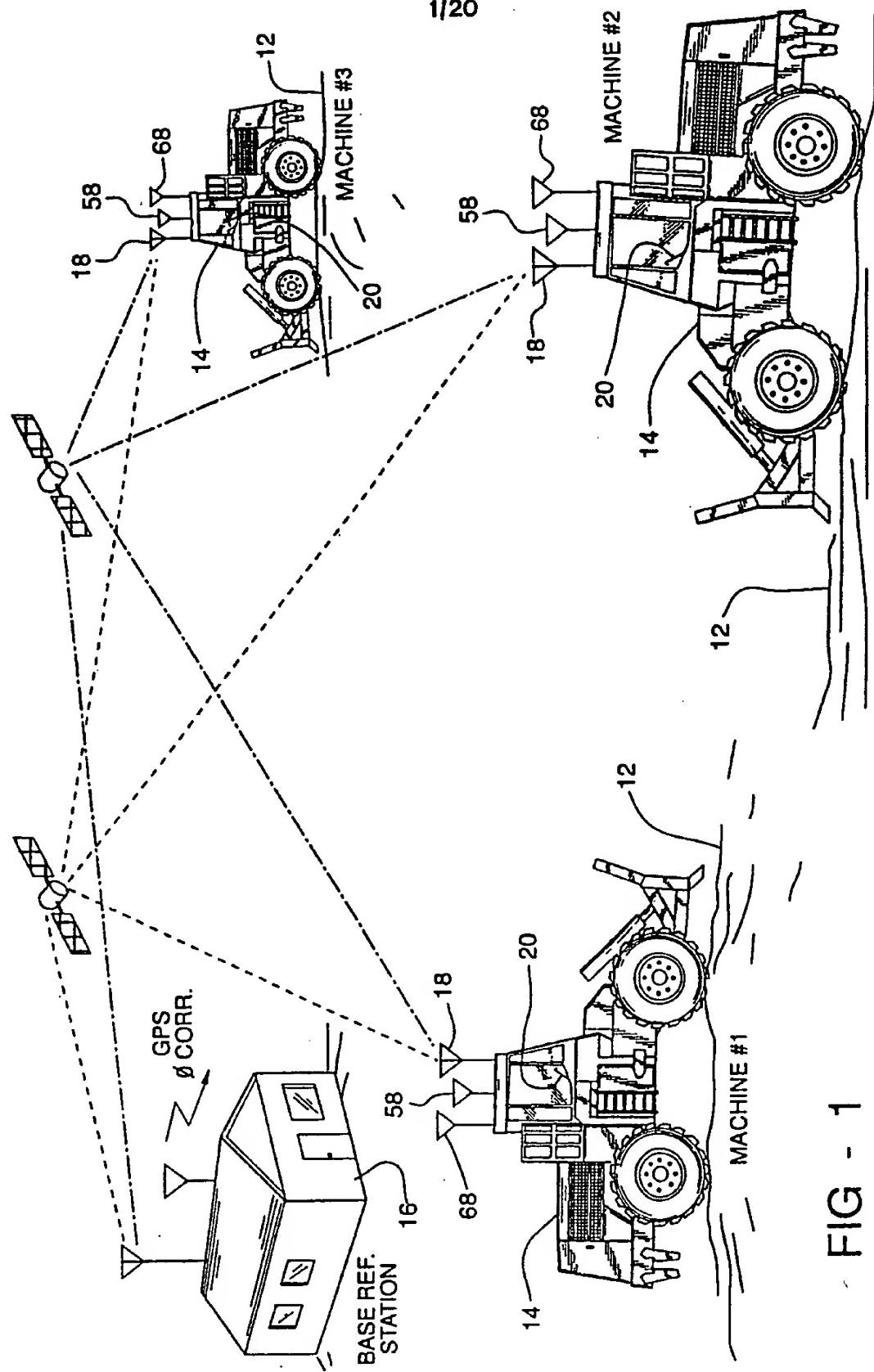


FIG - 1

FIG - 2

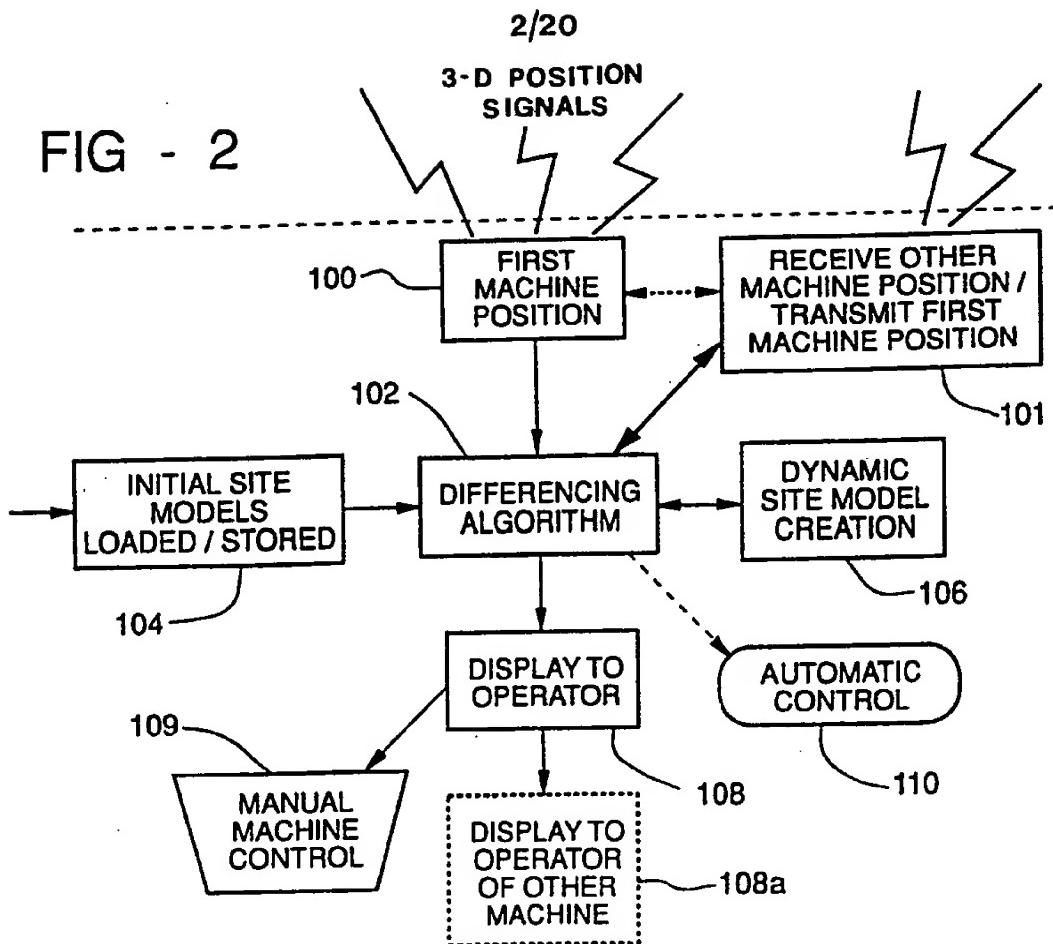
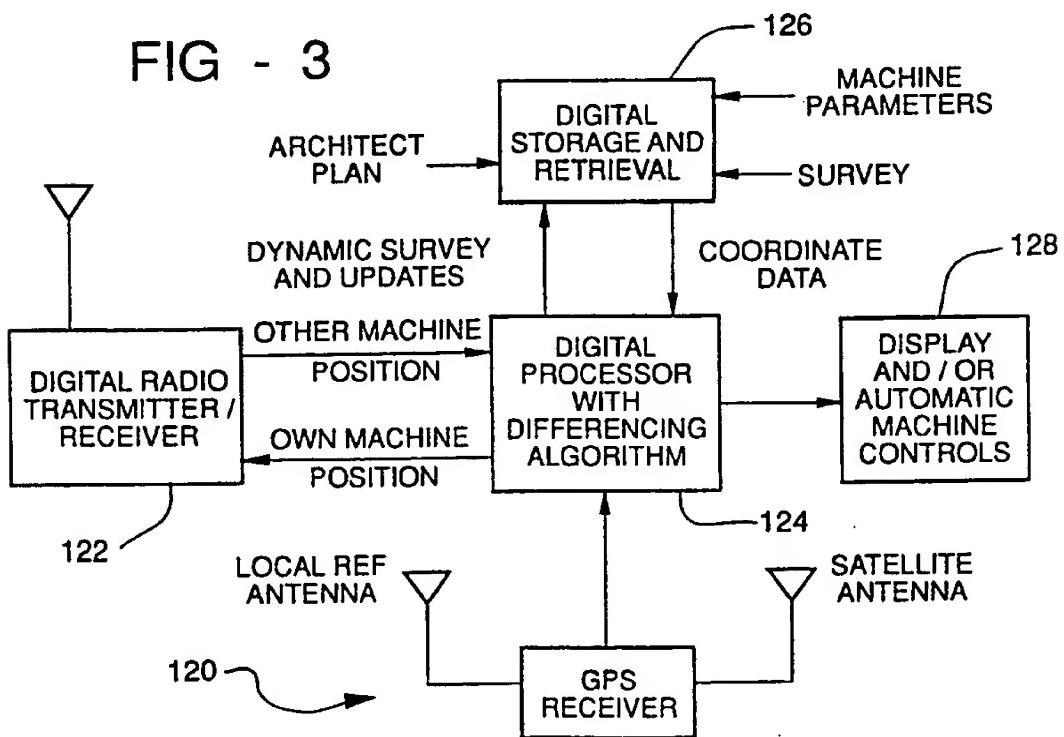


FIG - 3



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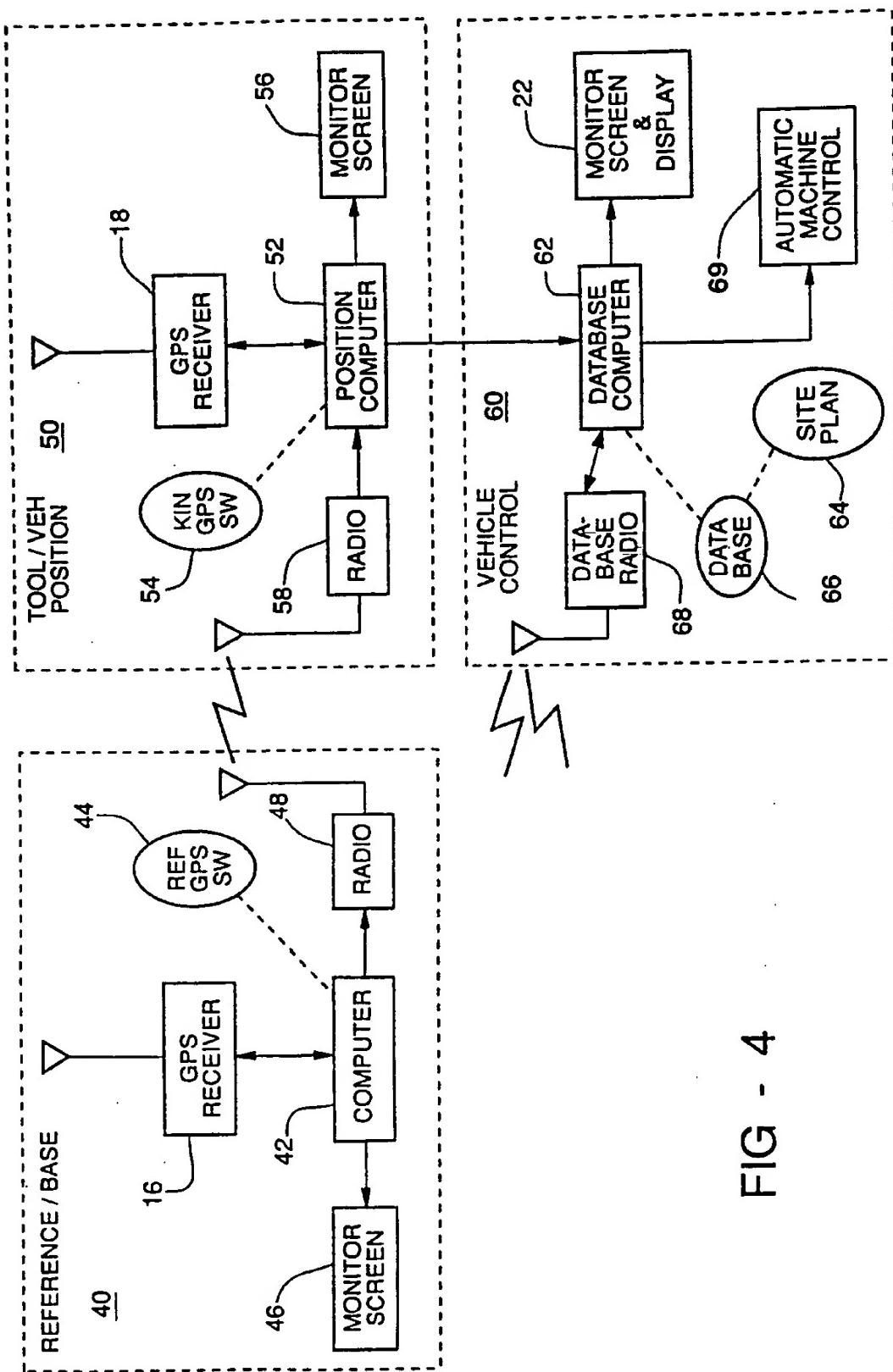


FIG - 4

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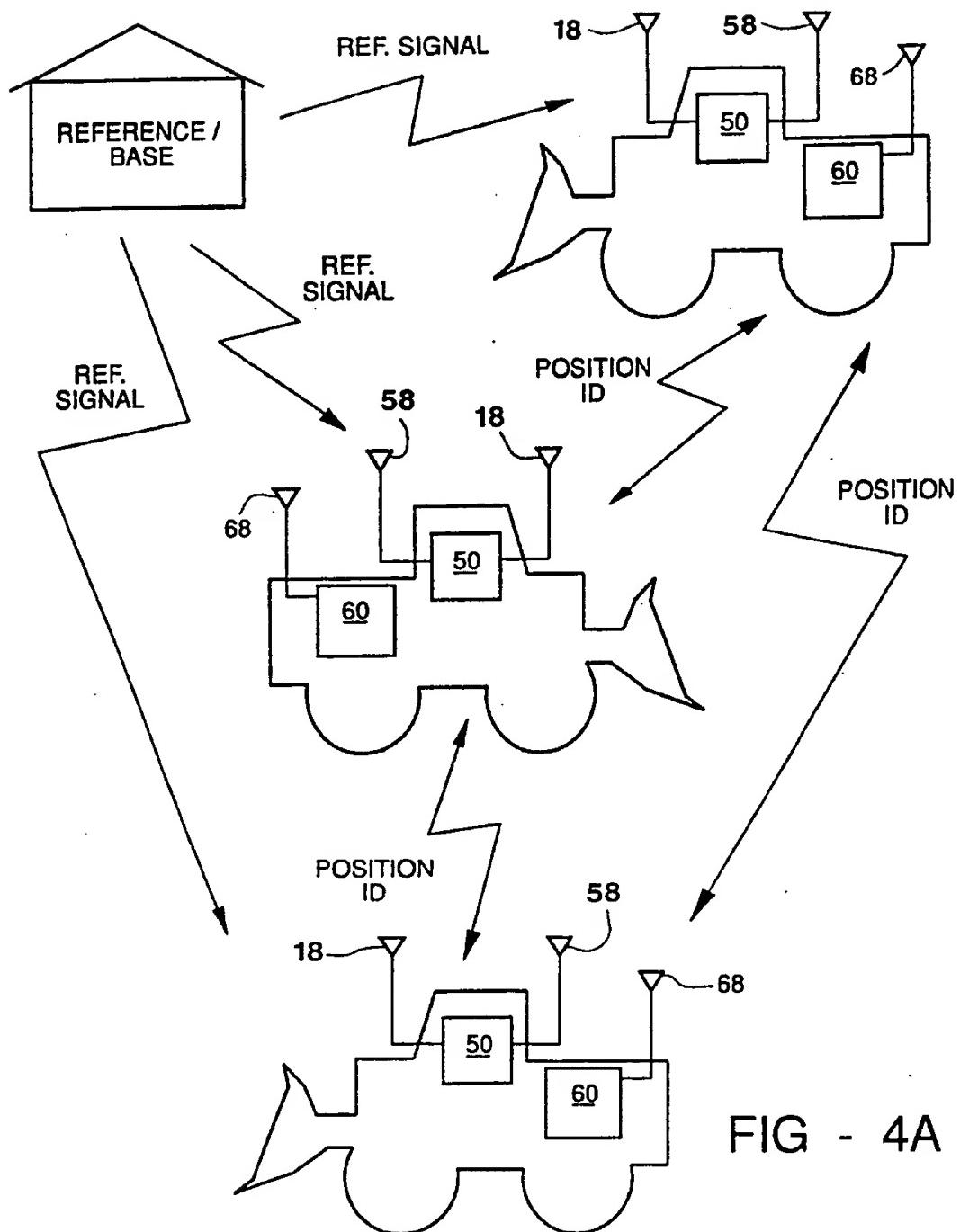
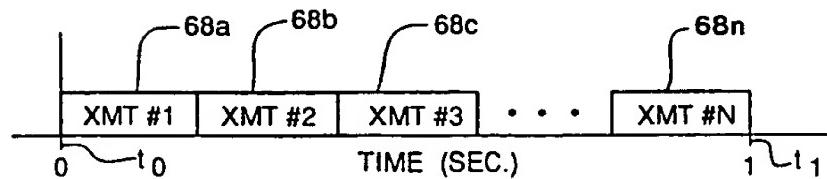


FIG - 4A

FIG - 5



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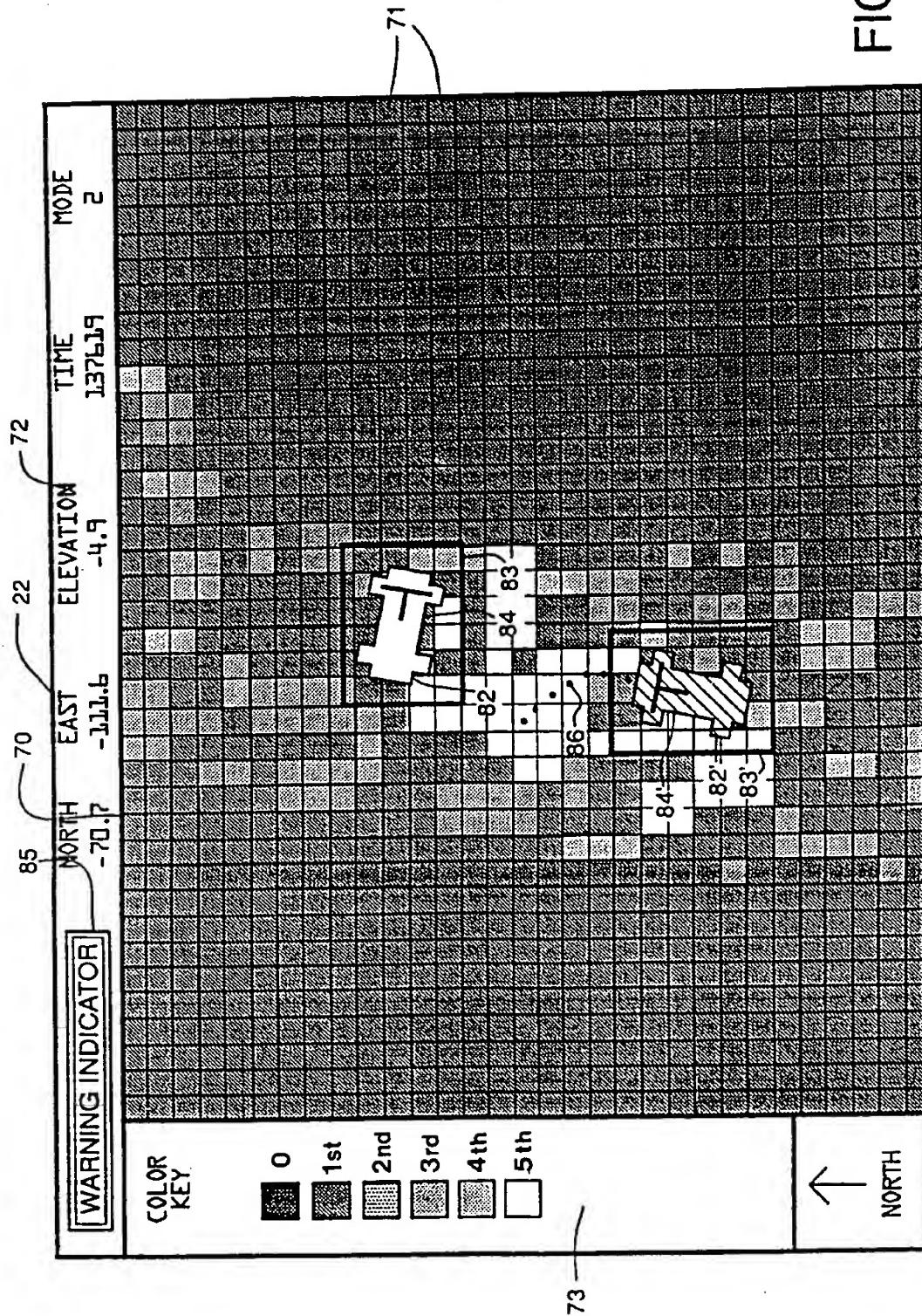
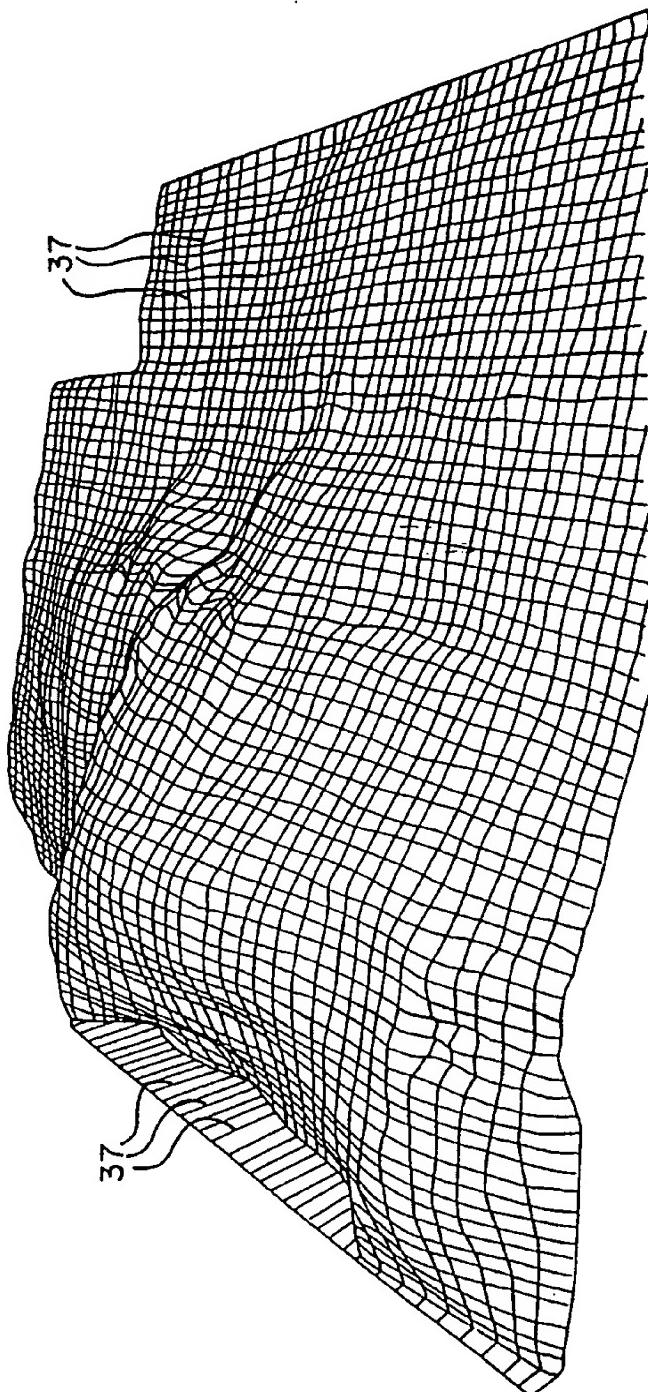


FIG - 6

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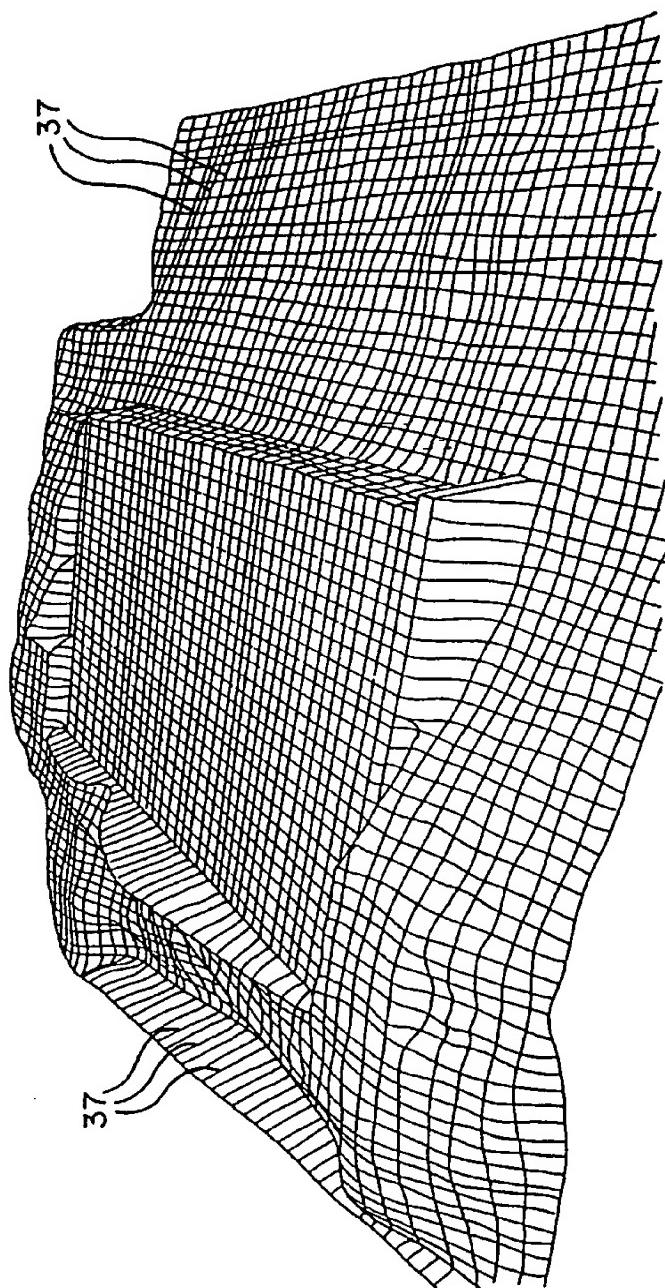
FIG - 6A



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FIG - 6B

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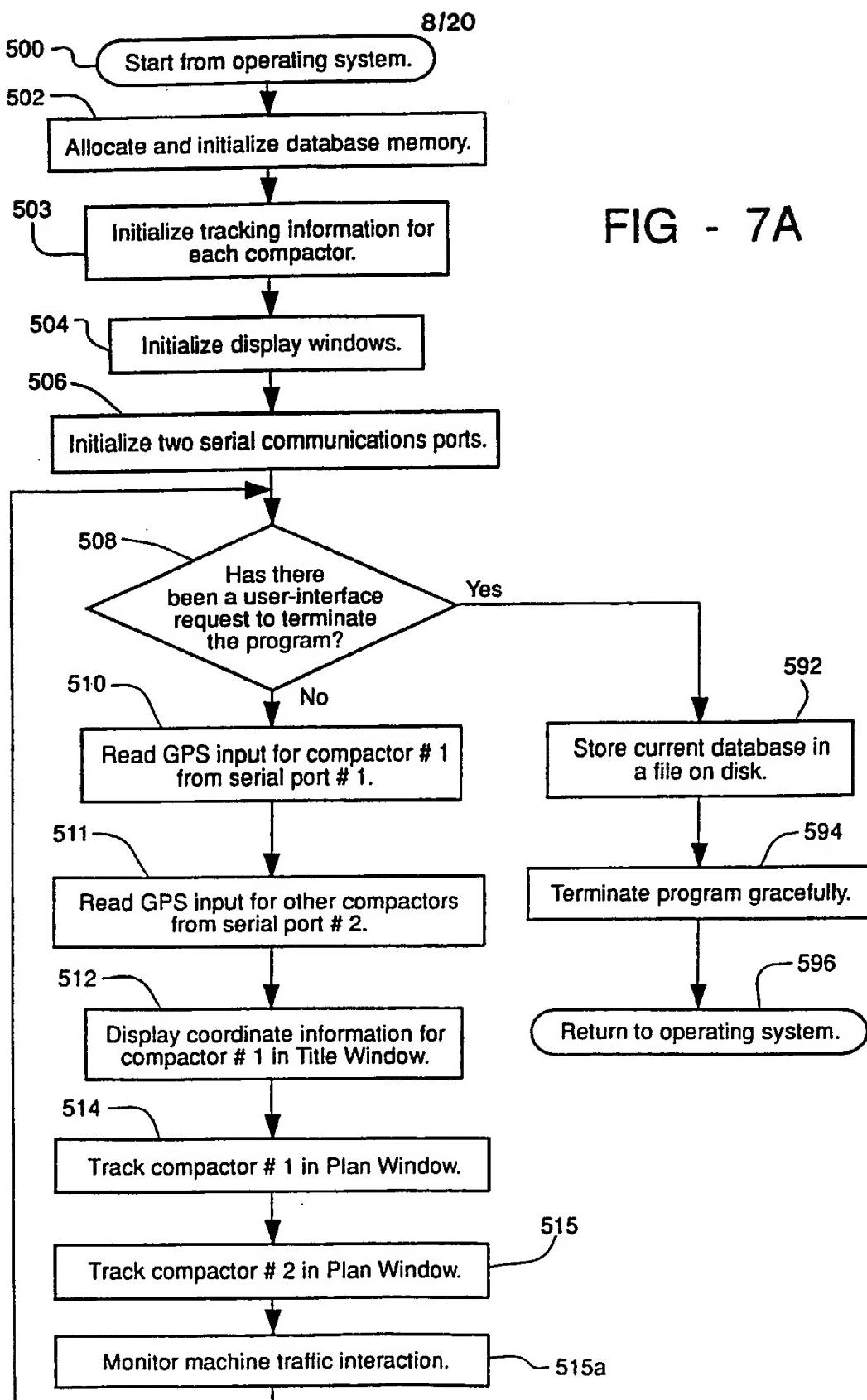
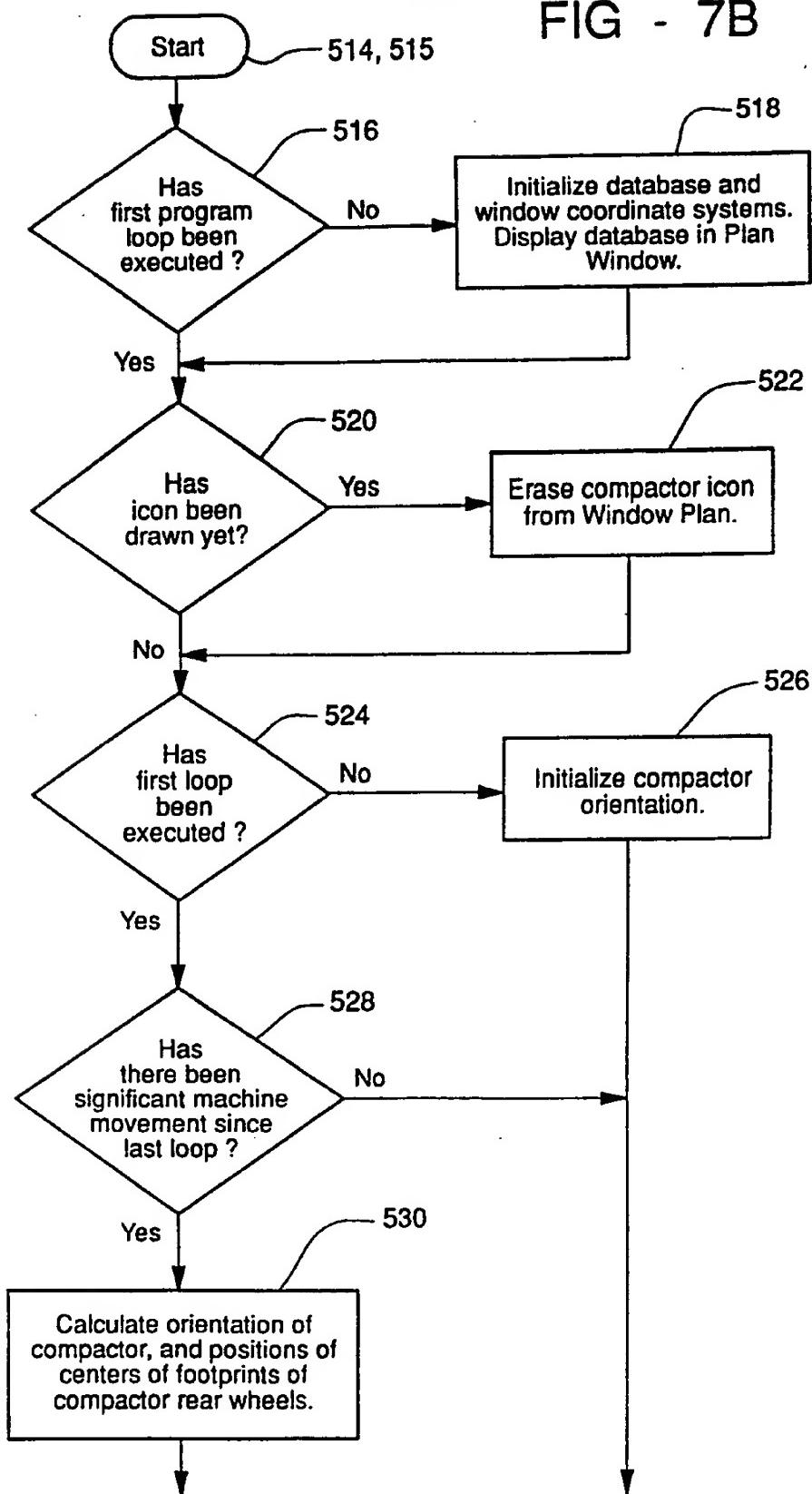


FIG - 7A

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## FIG - 7B



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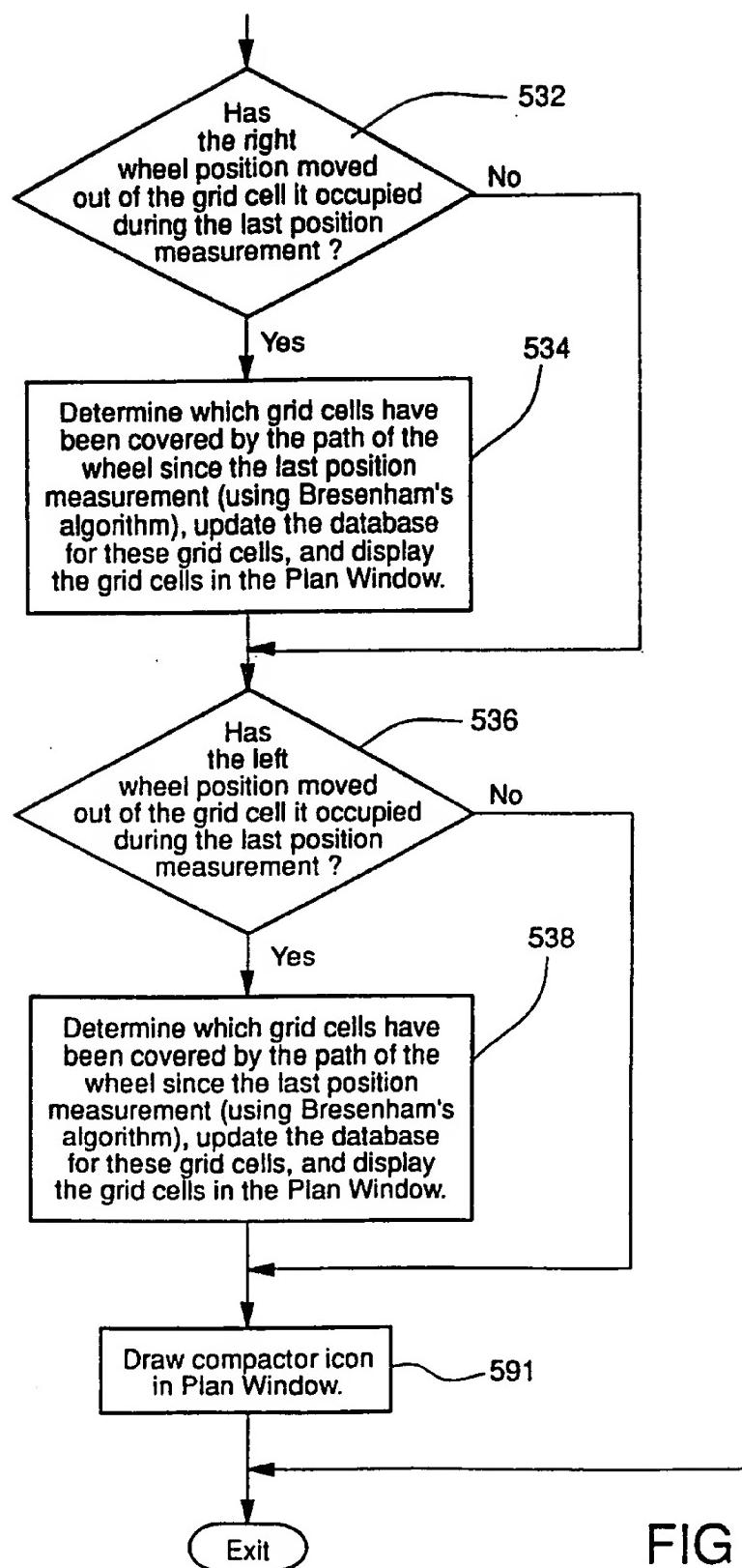
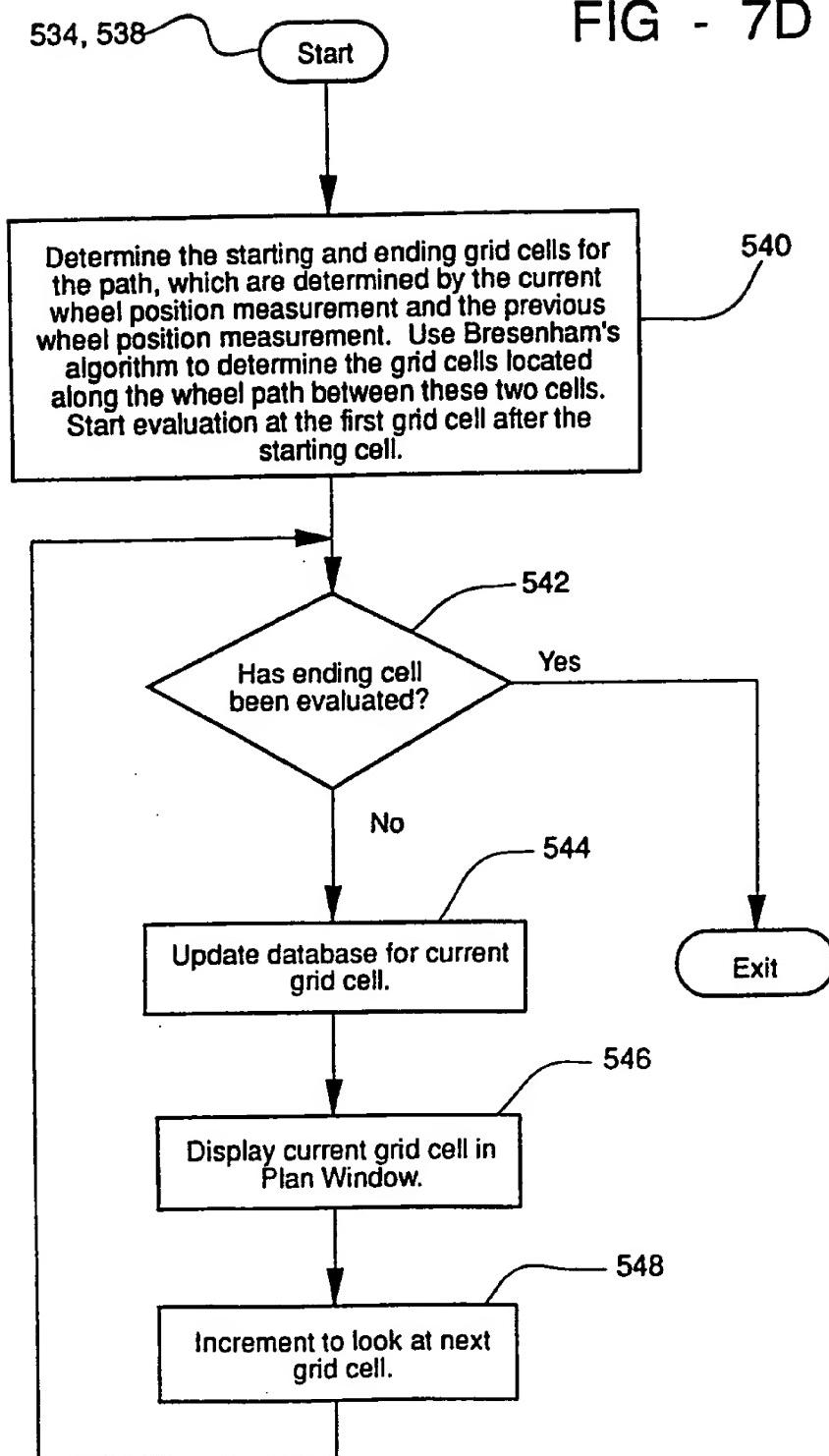


FIG - 7C

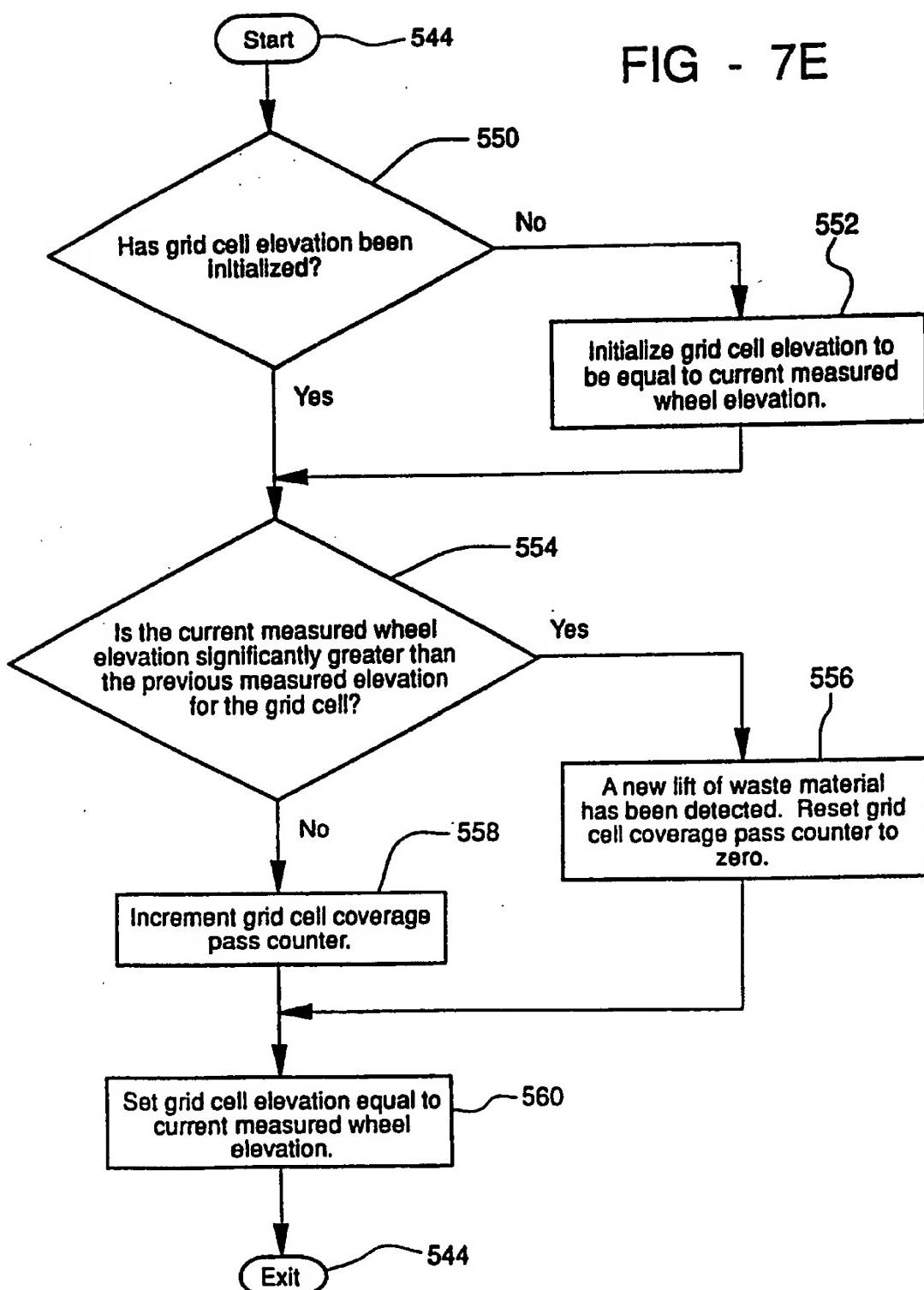
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FIG - 7D



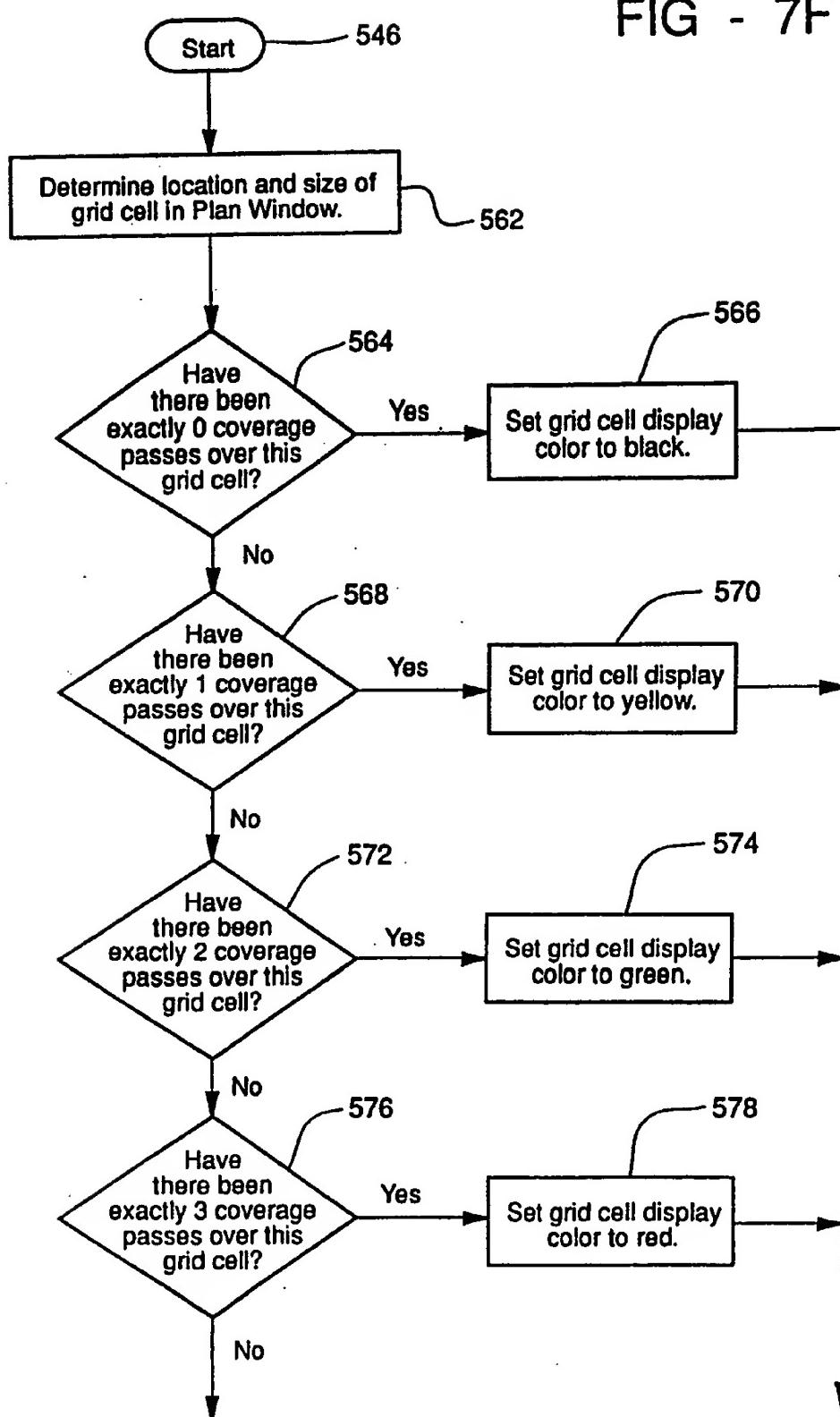
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FIG - 7E



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FIG - 7F



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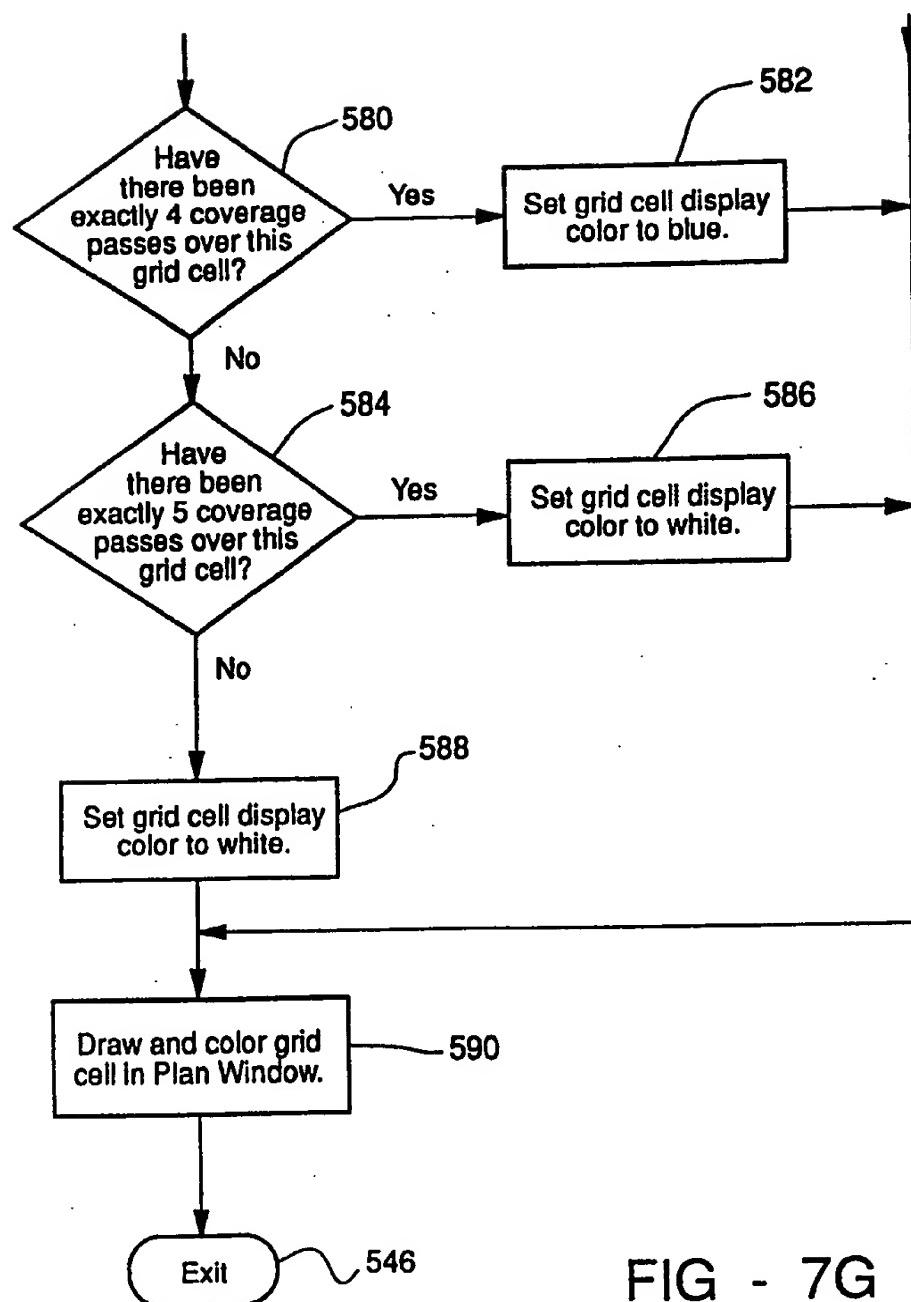
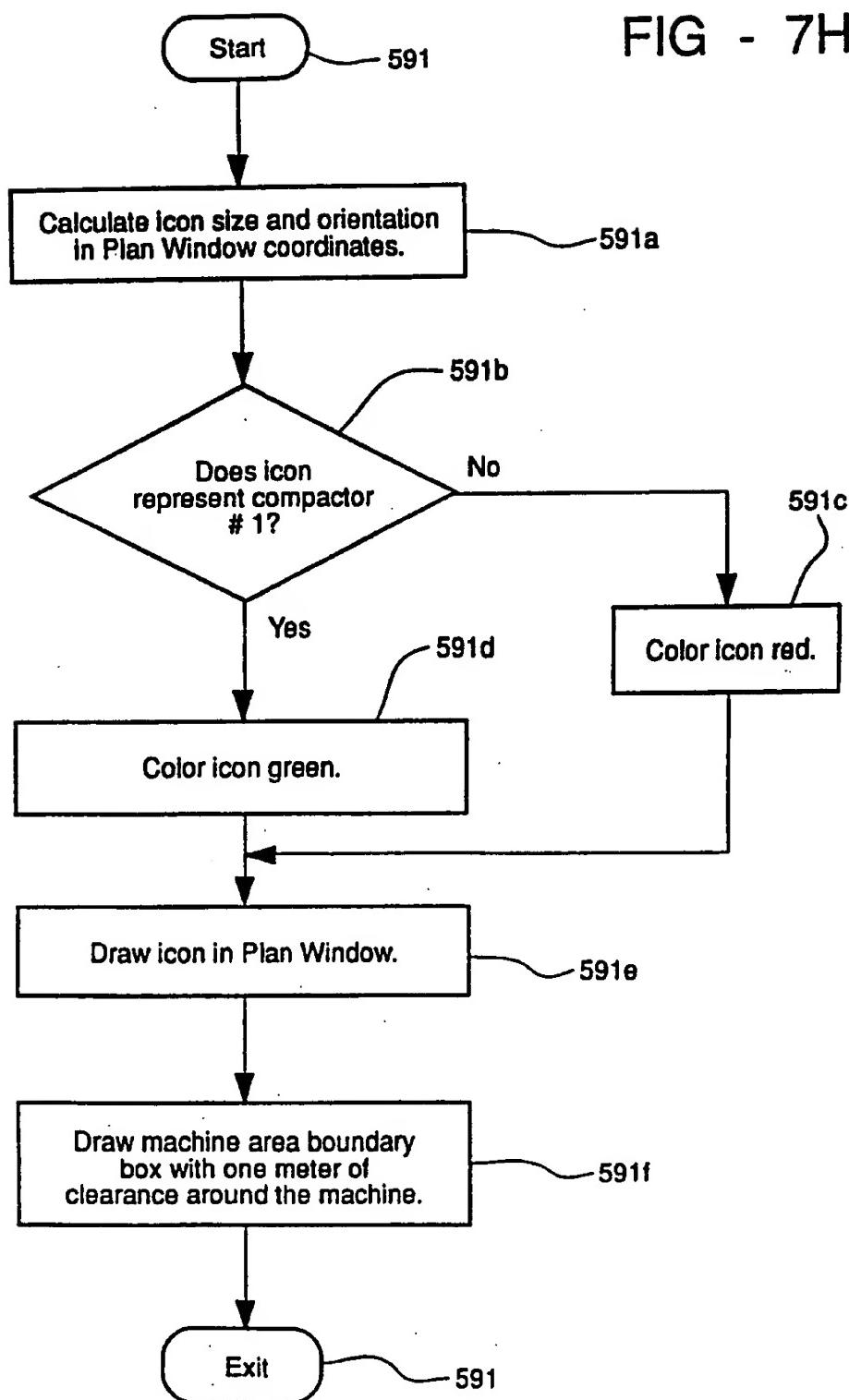


FIG - 7G

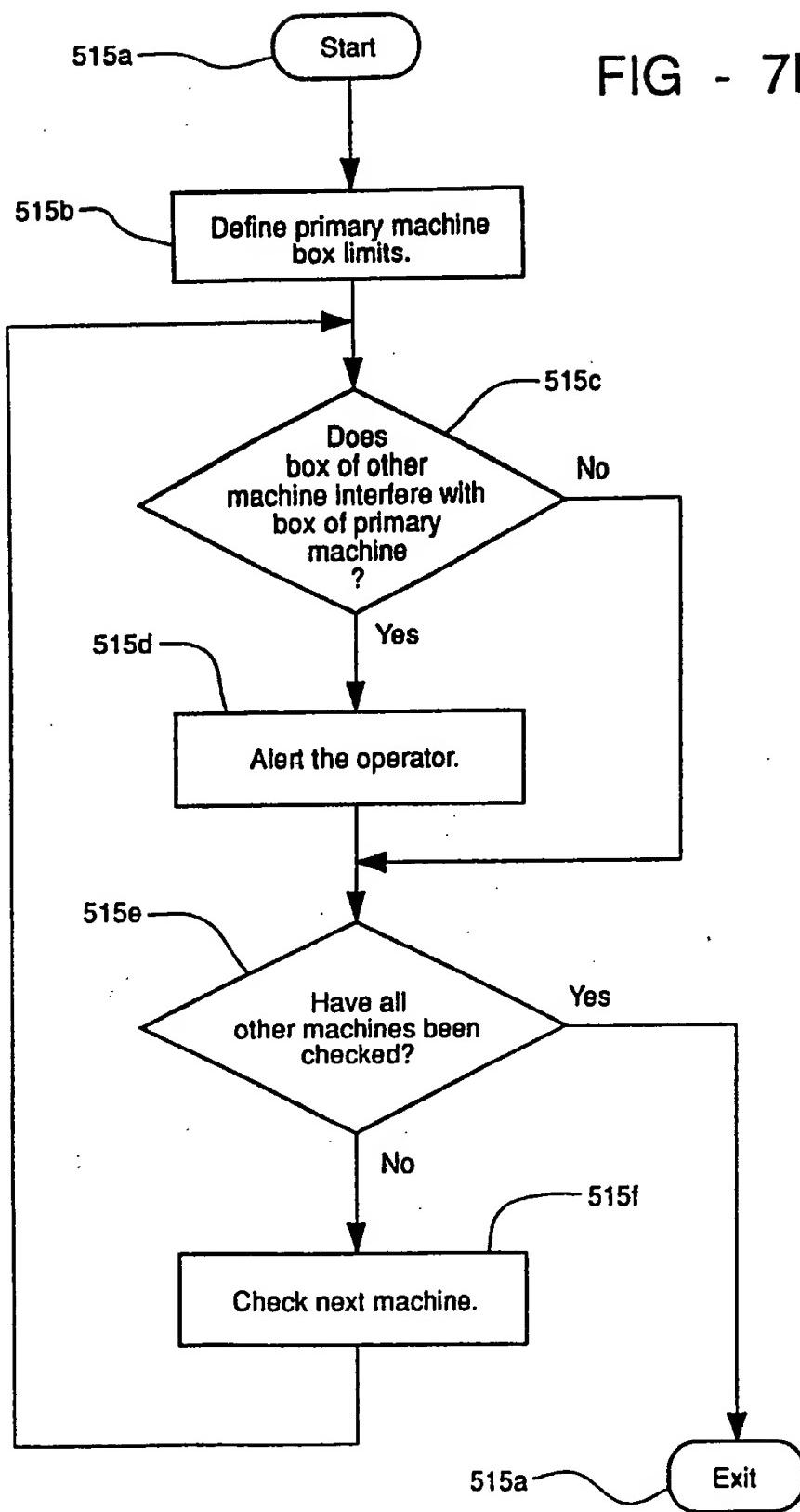
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FIG - 7H



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FIG - 7I



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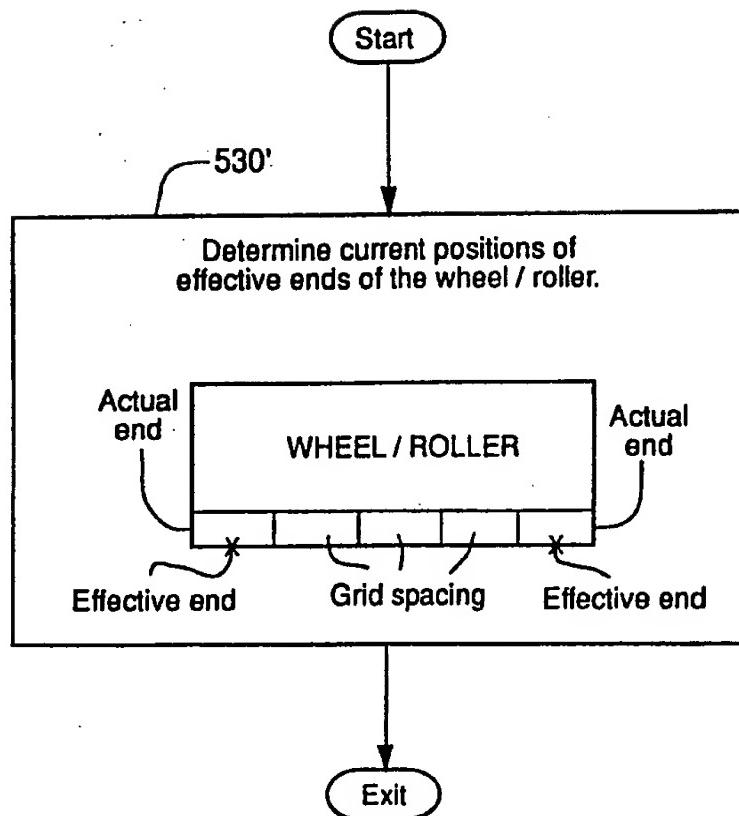
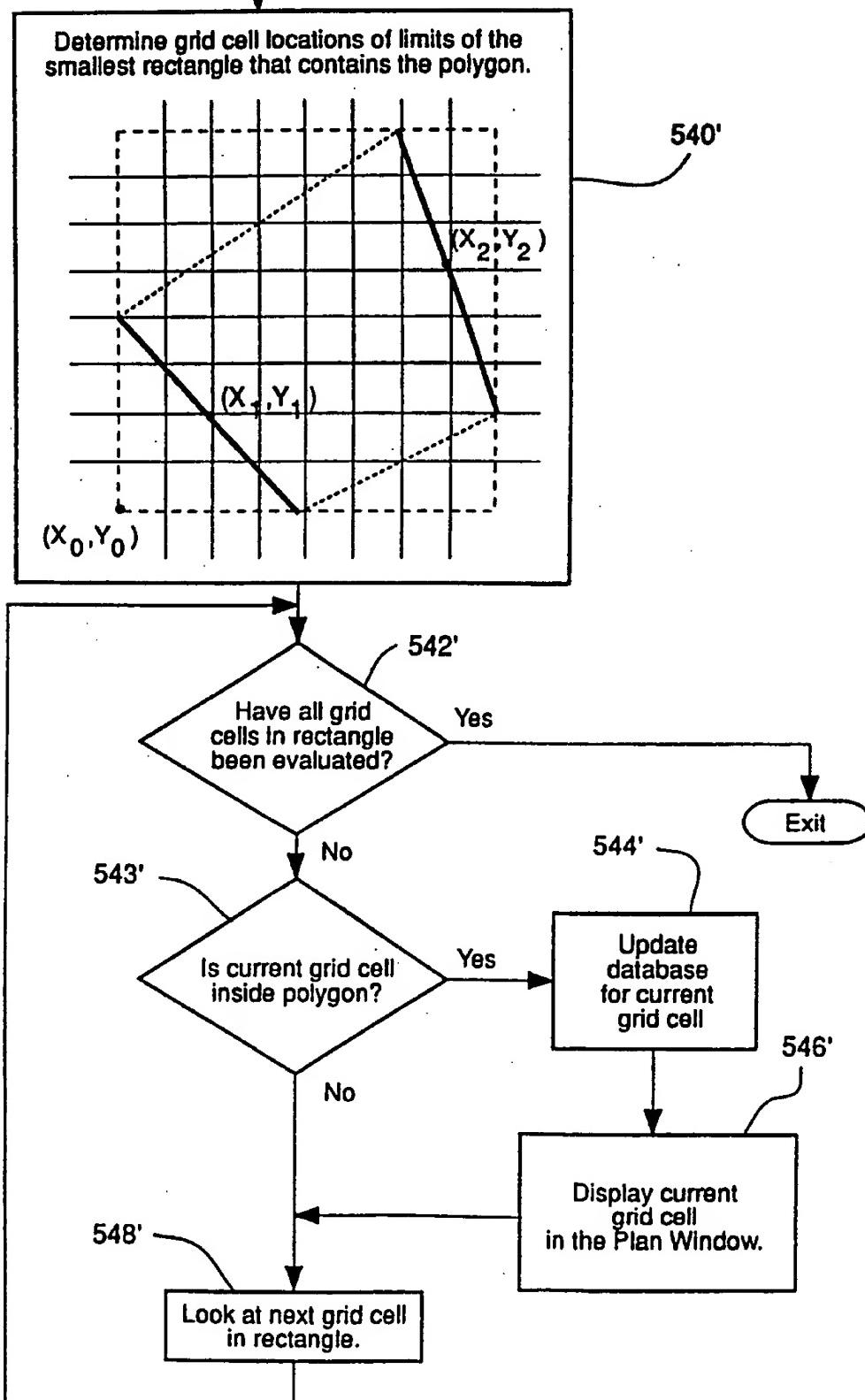


FIG - 7J

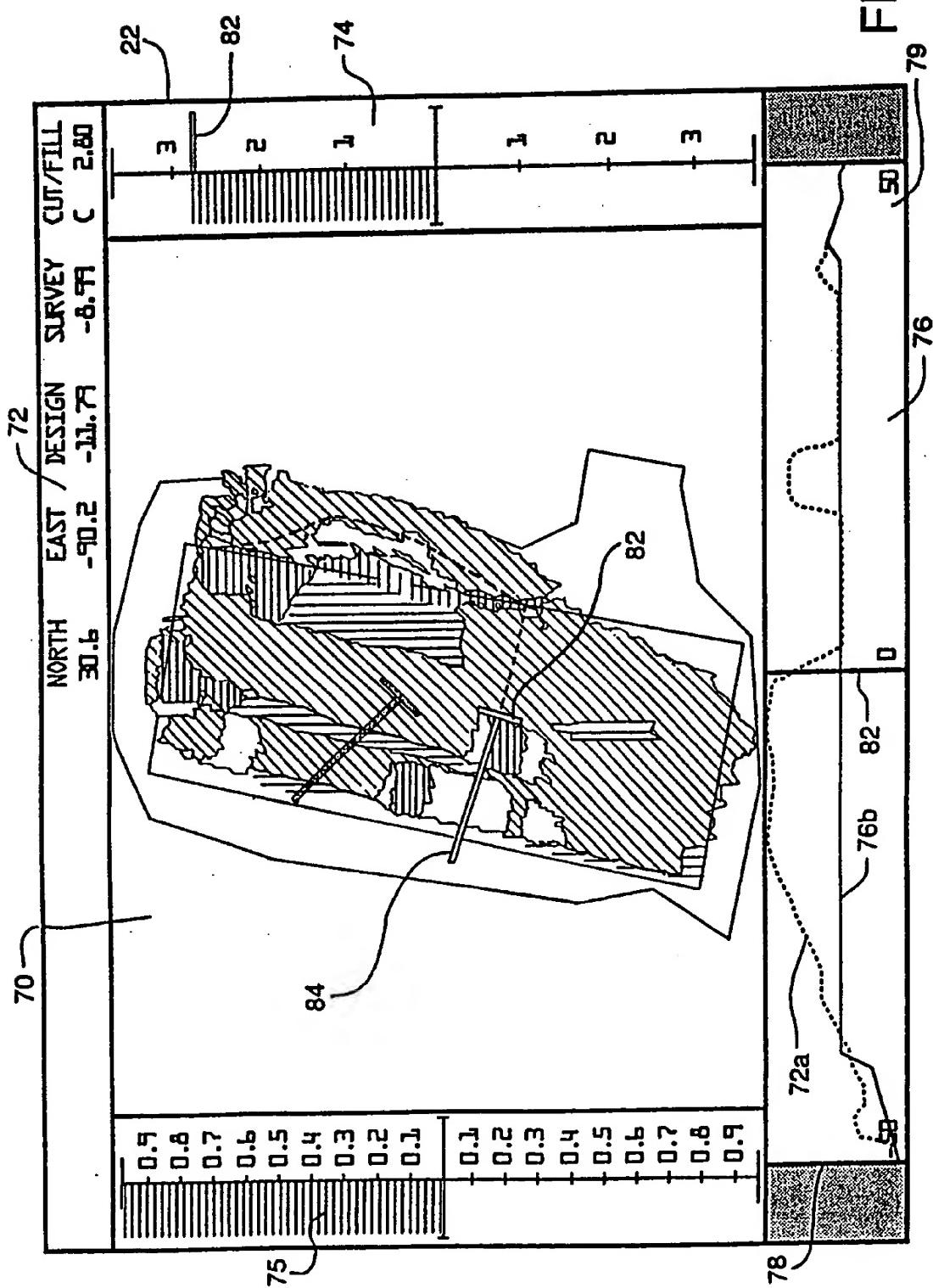
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FIG - 7K



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FIG - 8



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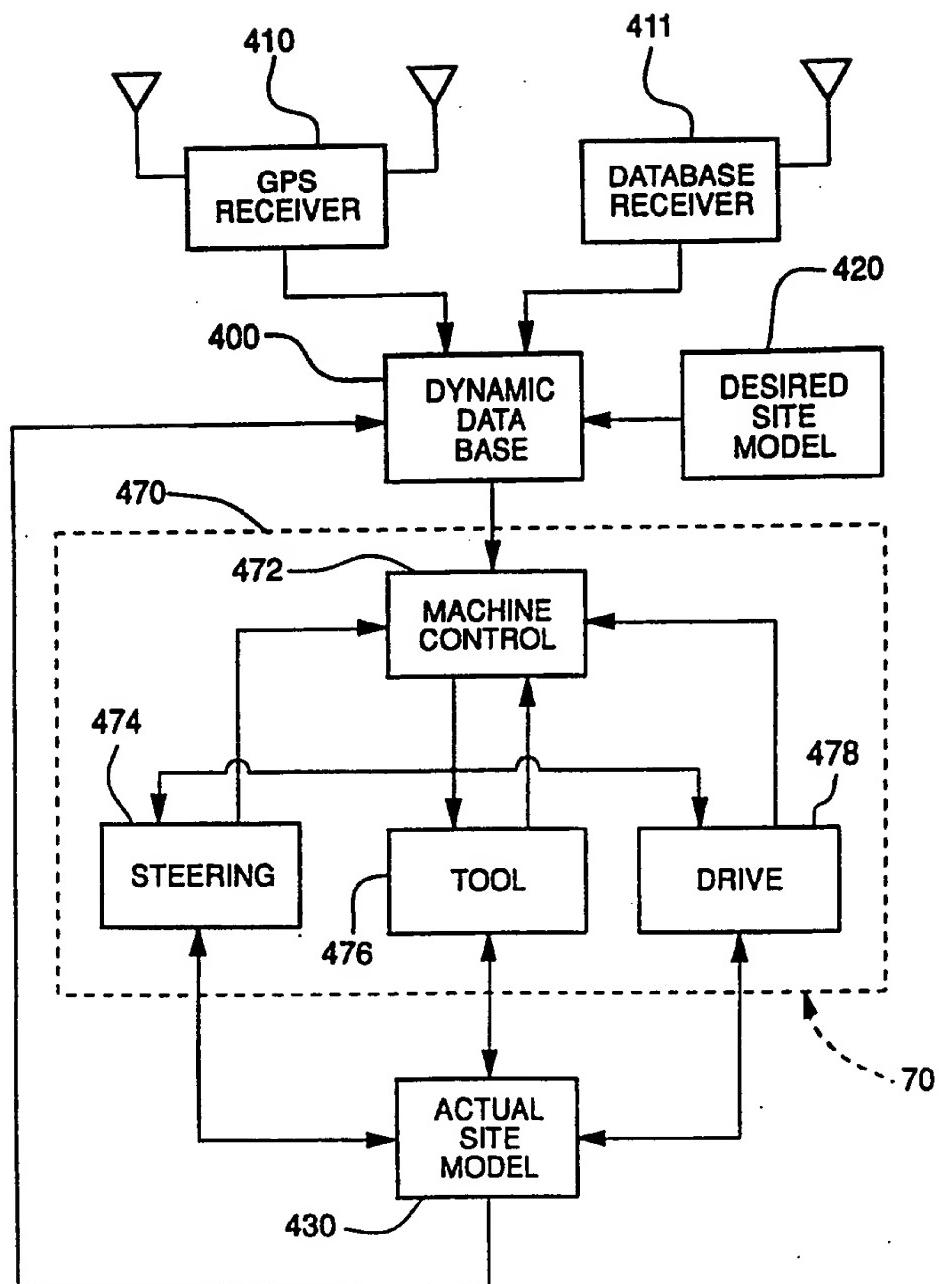


FIG - 9

**INTERNATIONAL SEARCH REPORT**

Inte. Application No  
PCT/US 95/04432

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 6 E01C19/00 E02F3/84

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)  
IPC 6 E01C E02F G05D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO-A-94 01812 (CONTRACTOR TOOLS) 20 January 1994 see the whole document -----	1-3,21
A	US-A-4 812 991 (MAGNAVOX) 14 March 1989 cited in the application see abstract -----	1

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

\*Special categories of cited documents :

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- "&" document member of the same patent family

Date of the actual completion of the international search

21 July 1995

Date of mailing of the international search report

02.08.95

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Authorized officer

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## INTERNATIONAL SEARCH REPORT

Information on patent family members

Int'l Application No  
PCT/US 95/04432

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9401812	20-01-94	AU-B- SE-A-	4594193 9202160	31-01-94 14-01-94
US-A-4812991	14-03-89	AU-B- AU-A- CA-A- DE-A- EP-A, B JP-T- WO-A-	590856 7435687 1268239 3776260 0264440 1501087 8706713	16-11-89 24-11-87 24-04-90 05-03-92 27-04-88 13-04-89 05-11-87